National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Services des thèses canadiennes

Ottawa, Canada
K1A 0N4

CANADIAN THESES

THÈSES CANADIENNES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

NL-339 (r.86/06)

Canada

THE UNIVERSITY OF ALBERTA

# IN-SOIL TRACTOR PERFORMANCE PREDICTION

by

(C) CONSTANTINOS KOTZABASSIS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA
SPRING 1986

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-315-30281-X

## THE UNIVERSITY OF ALBERTA

## RELEASE FORM

NAME OF AUTHOR CONSTANTINOS KOTZABASSIS

TITLE OF THESIS IN-SOIL TRACTOR PERFORMANCE PREDICTION

DEGREE FOR WHICH THESIS WAS PRESENTED MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED SPRING 1986

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(SIGNED) ............................

PERMANENT ADDRESS:

10 Adramitiou st
New Smyrni, Athens
HELLENIC REPUBLIC

DATED .March.27.,...1986

THE UNIVERSITY OF ALBERTA
FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled IN-SOIL TRACTOR PERFORMANCE PREDICTION submitted by CONSTANTINOS KOTZABASSIS in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in AGRICULTURAL ENGINEERING.

K W Domi.......................
Supervisor
..A.W. Anderson..
..D.S. Chanasyk..

Date..March 27.....1986

Οσοι το χαλκεον χερι
Βαρυ του φοβου αισθανονται
Ζυγον δουλειας ας εχωσι
Θελει αρετην και τολμην
Η Ελευθερια

Ανδρεας Καλβος

# ABSTRACT

One of the most important as well as controversial issues in Agricultural Engineering is the prediction of tractor performance under field conditions.

Prediction of tractor performance in-the-field requires knowledge of the following factors:

a. soil and its properties
b. traction devices and their properties
c. tractor design parameters.

Unfortunately, the work that has been carried out in the past is not complete enough to establish a firm grid of relationships as far as the three aforementioned factors are concerned.

The goals of this study were:

a. the presentation and analysis of each factor affecting tractor performance as an entity and in conjunction with the other factors
b. the development of in-soil tractor performance prediction models, using as input, tractor design and performance information, tire information, and Cone Index, and
c. the development of a computerized tractor analysis database management system featuring tractor data file Input/Output (I/O), simple regression analysis, graphics capabilities, the prediction

models and database management utilities.

For tractor analysis and prediction, a tractor analysis on concrete and three in-soil tractor performance prediction models were developed. The three models were titled ASAE D230.4, OECD (Organization for Economic Cooperation and Development), and HELLAS (High Efficiency Localized Locomotive Analysis-Simulation Software), respectively. The models were built according to the concept of the tractor as a *black box*.

The program aims in assisting a user to predict the in-field performance of a tractor whose performance is known on concrete. The program is presented and analyzed in terms of capabilities and reliability. Also the assumptions, under which the program is valid, are delineated.

# ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor and Head of the Agricultural Engineering Dept. Dr. *K.W. Domier* for his support, financial assistance and sharing of his valuable knowledge.

In addition, the author would like to specially thank *Αφροδιτη Καραμιτσανη* and *Βασιλη Καρανασιο* for being so supportive and caring throughout his stay in Canada.

# TABLE OF CONTENTS

Chapter Page

ABSTRACT....................................................vi

ACKNOWLEDGEMENTS..........................................viii

TABLE OF CONTENTS...........................................ix

LIST OF TABLES..............................................xv

LIST OF FIGURES............................................xvi

1. INTRODUCTION..............................................1

2. TERMINOLOGY...............................................9

3. FROM THE PAST TO THE FUTURE..............................13

4. LITERATURE REVIEW........................................25

  4.1. Soil and its properties..............................26

    4.1.1. What is soil?....................................27

    4.1.2. Structure, texture and soil constituents.........28

    4.1.3. Soil classification..............................29

    4.1.4. Theory of soil compaction........................31

    4.1.5. Soil strength and failure theories...............40

    4.1.6. Measuring soil properties........................43

      4.1.6.1. Soil strength................................43

      4.1.6.2. Bulk density and moisture content............51

      4.1.6.3. Soil stress status...........................52

      4.1.6.4. Cone Penetrometer and Cone Index.............53

    4.1.7. Soil bin facilities..............................61

  4.2. Traction devices and their properties................63

    4.2.1. Tire classification..............................63

Chapter Page

4.2.2. Rim and rim-tire matching........................66

4.2.3. Tire parameters..................................67

4.2.3.1. Tire size.....................................68

4.2.3.2. Ply rating....................................71

4.2.3.3. Inflation pressure............................71

4.2.3.4. Load factor...................................75

4.2.3.5. Lug parameters................................75

4.2.3.6. Tire effective arm and deflection.............77

4.2.3.7. Tire diameter.................................79

4.2.3.8. Tire width....................................80

4.2.4. Tire ballasting...................................80

4.2.5. Bias-ply versus radial tires......................85

4.2.6. Dual tires........................................89

4.3. Tractor design.......................................90

4.3.1. Primary tractor parameters.......................90

4.3.2. Residual tractor parameters......................93

4.3.3. Tractor field performance prediction.............101

4.3.4. Further developments.............................105

5. COMPUTER MODELS OF PHYSICAL SYSTEMS....................111

5.1. What is a computer model?...........................111

5.2. Computer models literature review...................112

5.3. Tractor analysis computer models....................116

5.4. Pros and cons of computer models....................120

5.5. Why use a microcomputer.............................122

5.6. The operating system................................124

5.7. BASIC...............................................124

Chapter Page

5.8. Database Management....126

6. TRACTOR ANALYSIS ON CONCRETE AND IN-SOIL TRACTOR PERFORMANCE PREDICTION....128

6.1. Introduction....128

6.2. On concrete tractor analysis input and output....128

6.3. Tractor analysis algorithm....131

6.4. Models input and output....137

6.5. Tractor performance prediction models....139

6.5.1. ASAE D230.4 model....139

6.5.2. Description of Zoz's graph....140

6.5.3. Implementation and model algorithm....140

6.5.4. Assumptions and limitations....140

6.5.5. Discussion....144

6.6.1. OECD model....144

6.6.2. Model algorithm....145

6.6.3. Assumptions....148

6.6.4. Limitations....149

6.6.5. Discussion....150

6.7.1. HELLAS model....151

6.7.2. Model algorithm....153

6.7.3. Discussion....154

6.8. Comparison of the models....154

6.9. Discussion....160

6.10.Conclusions....161

7. DATABASE MANAGEMENT SYSTEM FOR TRACTOR ANALYSIS....163

7.1. Software development....163

Chapter Page

7.2. Software attributes....................................167

7.3. Limitations............................................170

7.4. Software structure and implementation.................170

7.5. Program options........................................173

7.5.1. Display HELP facility...............................174

7.5.2. Create a new tractor file...........................174

7.5.3. Edit an old tractor file.............................176

7.5.4. Retrieve a database file.............................178

7.5.5. Run Graphics package................................180

7.5.6. Regression analysis algorithm.......................182

7.5.7. Run Simulation package..............................187

7.5.8. Serial Communications...............................187

7.5.9. Utility programs.....................................189

7.5.9.1. Tractor library utility...........................189

7.5.9.2. Tire library utility..............................191

7.5.9.3. File management utility..........................193

7.5.9.4. User defined program.............................193

7.6. Conclusions............................................193

8. SUMMARY AND CONCLUSIONS.................................195

9. RECOMMENDATIONS FOR FURTHER WORK.........................199

9.1. Introduction...........................................199

9.2. Programming techniques.................................199

9.3. Program scope..........................................199

9.4. Model experimental verification........................200

REFERENCES..................................................202

Abreviations................................................202

Chapter Page

List of References....................................203

APPENDIX A. GENERAL INFORMATION..........................223

Table A.1.............................................224

Table A.2.............................................226

Table A.3.............................................227

Table A.4.............................................227

Table A.5.............................................228

Table A.6.............................................229

APPENDIX B. NOMENCLATURE AND PROGRAM INFORMATION.........230

Table B.1.............................................231

Table B.2.............................................233

Table B.3.............................................237

Table B.4.............................................238

Table B.5.............................................240

Table B.6.............................................242

Table B.7.............................................244

Table B.8.............................................245

APPENDIX C. TRACTOR DATA SHEET AND SAMPLE OUTPUTS........246

Abreviations..........................................247

2WD Data sheet........................................248

FWA Data sheet........................................249

4WD Data sheet........................................250

2WD Travel Reduction..................................251

2WD Drawbar Pull......................................254

2WD Pull Ratio........................................257

2WD Tractive Efficiency...............................260

Chapter Page

FWA Travel Reduction....................................263

FWA Drawbar Pull........................................266

FWA Pull Ratio..........................................269

FWA Tractive Efficiency.................................272

4WD Travel Reduction....................................275

4WD Drawbar Pull........................................278

4WD Pull Ratio..........................................281

4WD Tractive Efficiency.................................284

Calibration curves......................................287

APPENDIX D. PROGRAM LISTING................................288

Program listing.........................................289

Programmer's note ......................................318

## LIST OF TABLES

Table Page

A.1. Standards, Data and Engineering Practices..........224

A.2. Agricultural Tractor Test Code (ASAE D230.4).......225

A.3. Approved Procedure for Rounding Data...............227

A.4. Index of Agricultural Section.......................227

A.5. Tire Coding Nomenclature...........................228

A.6. Unified Soil Classification System (USCS)..........229

B.1. IBM PC Hardware Design.............................231

B.2. HELLAS Integrated Software Subroutine Map..........233

B.3. Standard Format for Tractor Design Parameters......237

B.4. Display Tractor File Information...................238

B.5. List of Variables for Program Equations............240

B.6. Equations of the ASAE D230.4 Prediction Model......242

B.7. Equations Involved in the Calculation of the Motion Resistance Coefficient.............................244

B.8. Internal Structure of the Database Files...........245

C.1. Data Sheet for the FORD TW-20 2WD Tractor..........248

C.2. Data Sheet for the KUBOTA M5500 FWA Tractor........249

C.3. Data Sheet for the CASE 4890 4WD Tractor...........250

## LIST OF FIGURES

Figure Page

1.1 Triaxial representation of factors affecting tractor performance........................................6

4.1 Direct Shear Test Apparatus........................45

4.2 Triaxial Test Apparatus.............................47

4.3 Torsional or Ring Shear Test Apparatus..............50

4.4 Geometry of the Torsional or Ring Shear Test Apparatus.........................................50

4.5 Cone size versus penetration resistance.............58

4.6 Strength ratio versus penetration speed.............58

4.7 Radial ply tire construction.........................65

4.8 Bias ply tire construction...........................65

4.9 Definitions of tire dimensions.......................69

4.10 Free body diagram of a 2WD tractor..................94

4.11 Free body diagram of a 4WD tractor..................98

4.12 Static free body diagram of a single wheel.........100

4.13 Power transmission across the tractor..............106

6.1 Effect of wheel diameter on the coefficient of rolling resistance........................................133

6.2 Effect of pressure on the coefficient of rolling resistance........................................133

6.3 Sample load-deflection curve........................135

6.4 Zoz's graph - ASAE D230.4...........................141

6.5 ASAE D230.4 model flow-chart........................143

6.6 OECD model flow-chart...............................147

Figure Page

6.7 HELLAS model flow-chart....................152

7.1 DBMS - Ordinary database structure..................166

7.2 DBMS - Simulation database structure................166

7.3 Structural tree of the program....................168

7.4 Block diagram of the software....................171

7.5 Flow-chart of create routine....................175

7.6 Flow-chart of edit routine....................177

7.7 Flow-chart of retrieve routine....................179

7.8 Flow-chart of the Graphics package....................181

7.9 Flow-chart of the Simulation package....................188

C.1 2WD/TR/$S_1$/$I_1$ ....................251

C.2 2WD/TR/$S_1$/$I_2$ ....................251

C.3 2WD/TR/$S_1$/$I_3$ ....................251

C.4 2WD/TR/$S_2$/$I_1$ ....................252

C.5 2WD/TR/$S_2$/$I_2$ ....................252

C.6 2WD/TR/$S_2$/$I_3$ ....................252

C.7 2WD/TR/$S_3$/$I_1$ ....................253

C.8 2WD/TR/$S_3$/$I_2$ ....................253

C.9 2WD/TR/$S_3$/$I_3$ ....................253

C.10 2WD/DBPL/$S_1$/$I_1$ ....................254

C.11 2WD/DBPL/$S_1$/$I_2$ ....................254

C.12 2WD/DBPL/$S_1$/$I_3$ ....................254

C.13 2WD/DBPL/$S_2$/$I_1$ ....................255

C.14 2WD/DBPL/$S_2$/$I_2$ ....................255

C.15 2WD/DBPL/$S_2$/$I_3$ ....................255

Figure Page

C.16 2WD/DBPL/$S_3$/$I_1$ ....................................256

C.17 2WD/DBPL/$S_3$/$I_2$ ....................................256

C.18 2WD/DBPL/$S_3$/$I_3$ ....................................256

C.19 2WD/PR/$S_1$/$I_1$ ....................................257

C.20 2WD/PR/$S_1$/$I_2$ ....................................257

C.21 2WD/PR/$S_1$/$I_3$ ....................................257

C.22 2WD/PR/$S_2$/$I_1$ ....................................258

C.23 2WD/PR/$S_2$/$I_2$ ....................................258

C.24 2WD/PR/$S_2$/$I_3$ ....................................258

C.25 2WD/PR/$S_3$/$I_1$ ....................................259

C.26 2WD/PR/$S_3$/$I_2$ ....................................259

C.27 2WD/PR/$S_3$/$I_3$ ....................................259

C.28 2WD/TE/$S_1$/$I_1$ ....................................260

C.29 2WD/TE/$S_1$/$I_2$ ....................................260

C.30 2WD/TE/$S_1$/$I_3$ ....................................260

C.31 2WD/TE/$S_2$/$I_1$ ....................................261

C.32 2WD/TE/$S_2$/$I_2$ ....................................261

C.33 2WD/TE/$S_2$/$I_3$ ....................................261

C.34 2WD/TE/$S_3$/$I_1$ ....................................262

C.35 2WD/TE/$S_3$/$I_2$ ....................................262

C.36 2WD/TE/$S_3$/$I_3$ ....................................262

C.37 FWA/TR/$S_1$/$I_1$ ....................................263

C.38 FWA/TR/$S_1$/$I_2$ ....................................263

C.39 FWA/TR/$S_1$/$I_3$ ....................................263

C.40 FWA/TR/$S_2$/$I_1$ ....................................264

C.41 FWA/TR/$S_2$/$I_2$ ....................................264

Figure Page

C.42 FWA/TR/$S_2$/$I_3$ ....................................264

C.43 FWA/TR/$S_3$/$I_1$ ....................................265

C.44 FWA/TR/$S_3$/$I_2$ ....................................265

C.45 FWA/TR/$S_3$/$I_3$ ....................................265

C.46 FWA/DBPL/$S_1$/$I_1$ ....................................266

C.47 FWA/DBPL/$S_1$/$I_2$ ....................................266

C.48 FWA/DBPL/$S_1$/$I_3$ ....................................266

C.49 FWA/DBPL/$S_2$/$I_1$ ....................................267

C.50 FWA/DBPL/$S_2$/$I_2$ ....................................267

C.51 FWA/DBPL/$S_2$/$I_3$ ....................................267

C.52 FWA/DBPL/$S_3$/$I_1$ ....................................268

C.53 FWA/DBPL/$S_3$/$I_2$ ....................................268

C.54 FWA/DBPL/$S_3$/$I_3$ ....................................268

C.55 FWA/PR/$S_1$/$I_1$ ....................................269

C.56 FWA/PR/$S_1$/$I_2$ ....................................269

C.57 FWA/PR/$S_1$/$I_3$ ....................................269

C.58 FWA/PR/$S_2$/$I_1$ ....................................270

C.59 FWA/PR/$S_2$/$I_2$ ....................................270

C.60 FWA/PR/$S_2$/$I_3$ ....................................270

C.61 FWA/PR/$S_3$/$I_1$ ....................................271

C.62 FWA/PR/$S_3$/$I_2$ ....................................271

C.63 FWA/PR/$S_3$/$I_3$ ....................................271

C.64 FWA/TE/$S_1$/$I_1$ ....................................272

C.65 FWA/TE/$S_1$/$I_2$ ....................................272

C.66 FWA/TE/$S_1$/$I_3$ ....................................272

C.67 FWA/TE/$S_2$/$I_1$ ....................................273

Figure Page

C.68 FWA/TE/$S_2$/$I_2$ ....273

C.69 FWA/TE/$S_2$/$I_3$ ....273

C.70 FWA/TE/$S_3$/$I_1$ ....274

C.71 FWA/TE/$S_3$/$I_2$ ....274

C.72 FWA/TE/$S_3$/$I_3$ ....274

C.73 4WD/TR/$S_1$/$I_1$ ....275

C.74 4WD/TR/$S_1$/$I_2$ ....275

C.75 4WD/TR/$S_1$/$I_3$ ....275

C.76 4WD/TR/$S_2$/$I_1$ ....276

C.77 4WD/TR/$S_2$/$I_2$ ....276

C.78 4WD/TR/$S_2$/$I_3$ ....276

C.79 4WD/TR/$S_3$/$I_1$ ....277

C.80 4WD/TR/$S_3$/$I_2$ ....277

C.81 4WD/TR/$S_3$/$I_3$ ....277

C.82 4WD/DBPL/$S_1$/$I_1$ ....278

C.83 4WD/DBPL/$S_1$/$I_2$ ....278

C.84 4WD/DBPL/$S_1$/$I_3$ ....278

C.85 4WD/DBPL/$S_2$/$I_1$ ....279

C.86 4WD/DBPL/$S_2$/$I_2$ ....279

C.87 4WD/DBPL/$S_2$/$I_3$ ....279

C.88 4WD/DBPL/$S_3$/$I_1$ ....280

C.89 4WD/DBPL/$S_3$/$I_2$ ....280

C.90 4WD/DBPL/$S_3$/$I_3$ ....280

C.91 4WD/PR/$S_1$/$I_1$ ....281

C.92 4WD/PR/$S_1$/$I_2$ ....281

C.93 4WD/PR/$S_1$/$I_3$ ....281

Figure Page

C.94 4WD/PR/$S_2$/$I_1$ ....................................282

C.95 4WD/PR/$S_2$/$I_2$ ....................................282

C.96 4WD/PR/$S_2$/$I_3$ ....................................282

C.97 4WD/PR/$S_3$/$I_1$ ....................................283

C.98 4WD/PR/$S_3$/$I_2$ ....................................283

C.99 4WD/PR/$S_3$/$I_3$ ....................................283

C.100 4WD/TE/$S_1$/$I_1$ ....................................284

C.101 4WD/TE/$S_1$/$I_2$ ....................................284

C.102 4WD/TE/$S_1$/$I_3$ ....................................284

C.103 4WD/TE/$S_2$/$I_1$ ....................................285

C.104 4WD/TE/$S_2$/$I_2$ ....................................285

C.105 4WD/TE/$S_2$/$I_3$ ....................................285

C.106 4WD/TE/$S_3$/$I_1$ ....................................286

C.107 4WD/TE/$S_3$/$I_2$ ....................................286

C.108 4WD/TE/$S_3$/$I_3$ ....................................286

C.109 Calibration curve for Travel Reduction.............287

C.110 Calibration curve for Tractive Efficiency..........287

# 1. INTRODUCTION

Farming is a three thousand year old process which first evolved in the countries around the eastern Mediterranean sea. Civilizations like Egyptian, Babylonian, Assyrian and Hellenic developed farming employing oxen and horses. At that time the implements in use were made out of wood and iron (Isiodian plow). During the sixteenth century, when North America's settlement started, horses and oxen were used both for transportation and implement drawing. Four or more animals were used for farming operations, providing increased drawbar pull. During the transition from the "Homesteader's Ox" to the steam engine the "Battle of Breeds" dominated the building of the Western agricultural empire. Battle of Breeds was the name given to the dispute concerning horse breed superiority. The underlying fact was the desperate need of the homesteader for more farm power (MacEwan, 1974).

The first steam application was credited to Hero of Alexandria. The work of Otto von Guericke, Thomas Newcomen, and James Watt opened new horizons for the world. Richard Trevithick in England was credited with the application of steam to move an engine on rails just after 1800. Canadian farmers started using stationary steam engines during the second half of the nineteenth century. Many of these machines carried the "Eagle" engine, trade mark of J.I.

Case. In 1855 the American farmer J. McCune connected his portable steam engine to the truck wheels on which it was mounted, thus providing self power for moving. In 1869 Case offered an 8 HP portable steam engine known as Old Number One and an improved thresher bearing the name "Eclipse". In 1876 Case presented a steam tractor ready for the market and good enough to win a gold medal at Philadelphia and later at Paris (MacEwan, 1974).

The era of harnessing mechanical power for agricultural use was a reality and the tractor started formatting. Through the years technology will improve the tractor but will not change the major tractor design characteristics. Regardless of the tractor's bulk, awkwardness of design and low efficiency that characterized every design in its early steps there was one feature worth mentioning. The tractive devices were wide steel wheels with lugs, forecasting the modern tread bars of the rubber tires. The concept of the grip was evident.

Ever since the early years of tractor appearance the question was "how can the overall tractor performance be maximized?" A significant step towards tractor performance improvement was the substitution of steel wheels with rubber tires. Rubber tires were introduced in agriculture after their use both in the car and airplane industries (Larsen, 1981).

For a few years following the introduction of rubber tires in the mid-1930's, the people involved in the agricultural industry sustained a controversy concerning the tractive performance superiority of steel wheels compared to wheels equipped with rubber tires. Contemporary tractors indicate the winning trend.

During the years tractor design was improved, resulting in increased reliability and durability. However, tractor performance did not show the same rates of improvement. At that time the importance of knowledge of the soil and traction device properties became clear to the tractor manufacturers. This observation led the researchers in a high activity around three centers of interest which at the same time were centers of technology. These centers had different perspectives and they were:

a. educational institutions studying the soil and its properties from a scientific point of view

b. tire companies testing the existing tires and developing new generations of tires, and

c. tractor companies employed in the difficult task of tractor design development.

The time invested in research for a number of years was characterized by the lack of coherence in the endeavors of these centers of research. Though a significant amount of information was produced and processed, the results obtained did not advance the state of technology as much as expected. The prediction models developed and submitted for use in the industry were limited to individual areas of study and had no information to add to the final purpose, which is tractor performance improvement based on a global knowledge of tractor environment relationships. Another research related problem was the lack of standardization, that devastated the agricultural market for a number of years.

Standardization in Agricultural Engineering was started in 1909 by the American Society of Agricultural Engineers (ASAE) with the appointment of the Committee of Standardization of Farm Machinery, Farm Tractors and Their Tests. Since then the ASAE Standards are updated yearly and constitute the guideline for the agricultural industry. The most important feature of the standardization process is the cooperation in the endeavors of the industry and the educational institutions towards tractor development and consequently tractor performance improvement.

Tractor performance encompasses traction device performance, since soil-wheel interaction is the factor that makes the tractor's capabilities useful. The overall tractor performance is directly dependent on tractor design and tire performance. Optimization of the tractor design parameters is not sufficient to boost the overall tractor performance. The selection of the appropriate tire in terms of its design characteristics (size, ply rating, lug angle, etc.) is crucial in order to establish a close matching with both tractor and terrain. If this link is defective the overall tractor performance will be very poor regardless of the tractor's capabilities. However, an accurate model of the traction characteristics of rubber tires on a deformable surface is yet to be accomplished (Domier and Willans, 1979a).

So far the term "tractor performance" has been used extensively but has not yet been defined. Tractor performance comprises a number of parameters providing information on how efficiently the tractor operates under a specific tractor design - traction device - soil condition combination. The most common parameters that determine tractor performance are Tractive Efficiency, Dynamic and Gross Traction Ratios, Force Efficiency, forward velocity, slip, Drawbar Pull and Drawbar Power. The aforementioned parameters can be plotted against slip and indicate the optimum operating conditions of a tractor in a specific field. Comparing the actual and optimum operating conditions of a tractor, various recommendations can be made for optimization, among which are engine speed, gear selection, and ballast estimation.

Initially, the goal was the estimation of tractor performance as a composite vector in three-dimensional space. A comprehensive illustration of the tractor performance in terms of soil properties, tire characteristics and tractor design in the three-dimensional space is shown in Figure 1.1, where:

i. one axis would represent the soil factor
ii. one axis would represent the tire factor
iii. one axis would represent the tractor design factor.

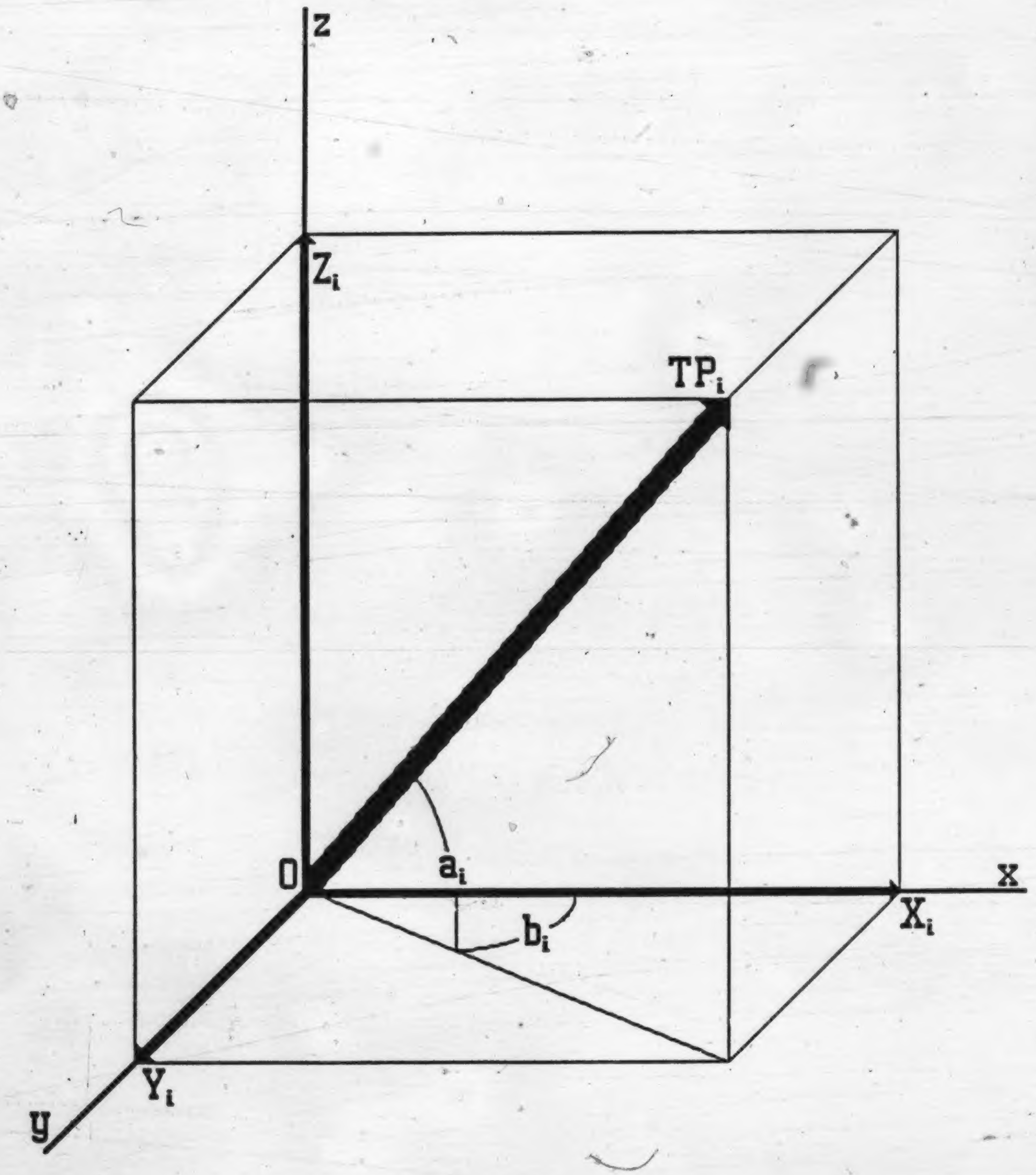

z
$Z_i$
$TP_i$
0
$a_i$
x
$b_i$
$X_i$
$Y_i$
y

Figure 1.1 Triaxial representation of factors affecting tractor performance

Then the tractor performance of a specific tractor equipped with a specific set of tires on a specific soil would have been represented by a definite point in the space, having axial coordinates $(X_i, Y_i, Z_i)$ and polar coordinates $(TP_i, a_i, b_i)$. When polar coordinates were to be used, $TP_i$ would refer to the magnitude of a tractor performance equivalent vector and $a_i$ and $b_i$ would have been angles determining the vector's orientation in space. The important feature of this geometrical space would have been that the tractor performance, soil factor, tire factor and tractor design factors could be represented by non-dimensional vectors expressed as a function of performance. Tractor performances, represented by vectors of the same magnitude should have the same rating in terms of performance.

The soil properties can be expressed as an index, using the Cone Index value. The traction device properties can be expressed as an index, using the tire specifications. The tractor design parameters can be expressed as a tractor performance related index using engine speed, gear setting and ballast.

Using the three indexes and a subjective interpretation of the indexes, a tractor performance evaluation expressed as a single number can be obtained. However, different criteria are used to evaluate tractor performance, thus a n-dimensional space would be required to describe tractor performance in terms of important parameters, such as forces, powers, ratios and efficiencies. In light of the subjective selection of the important tractive performance parameters the output of the program is a n-dimensional space and the tractor performance evaluation is left to the user's judgement of which tractor performance parameter is important and which is not. A detailed description of the inputs and the output of the models is provided in the sixth chapter.

The goals of this study include the presentation and analysis of the factors affecting tractor performance, the development of a model for in-field tractor performance prediction, and the development of a complete application oriented database management system, built around three prediction models. Towards in-field tractor performance prediction three models were taken into consideration. The first model was based on the work first presented by Zoz (1972) and is also included in ASAE D230.3 (1984). The second model was based on an in-field tractor performance prediction model developed for the Organization for Economic Cooperation and Development (1984). The third model was based on widely acceptable equations describing in-field tractor performance. The inputs to the program include Cone Index, tire information and tractor information. Tractor and tire information are provided through available libraries created for the needs of the application.

## 2. TERMINOLOGY

Standardization in the agricultural industry demanded and therefore developed an extensive terminology. The Standards presented by ASAE cover a wide variety of topics and they are the product of the combined efforts of the people employed both in industry and in educational institutions.

On the other hand organizations with a different scope, like the Society of Automotive Engineers (SAE) and The Tire and Rim Association Inc. (TRA), have also presented standards related to Agricultural Engineering. According to ASAE terminology the standards are classified according to a number and a letter in front of the classification number. The letters represent Standards (S), Data (D) or Engineering Practices (EP). Where applicable, the SAE classification number is appended to the ASAE classification number.

In introducing the ASAE Standards-1984 a reference to the unit system is required. The official ASAE unit system is the International System of Units (System Internationale d'Unites, SI). If English units are to be referenced, they will normally follow the SI units in brackets. The Engineering Practice EP285.6 refers to the use of SI units.

As far as Power and Machinery is concerned, the most important Standards, Data and Engineering Practices are presented in Appendix A, Table A.1. Soil strength is measured with the Soil Cone Penetrometer, whose description is given in the ASAE S313.1.

The Society of Automotive Engineers in contributing to the standardization process has devoted Volume 4 of the 1984 SAE Handbook to On-Highway Vehicles and Off-Highway Machinery. The standards included in the SAE Handbook are compatible with these presented in ASAE Standards-1984. SAE Standards, Recommended Practices, or Information Reports with regard to surface vehicles begin with a designation consisting of the letter "J" followed by a number (SAE Handbook, 1984). The SAE designation is shown between brackets following the ASAE coding in the list given in Appendix A, Table A.1.

A reference source of terminology and tire information is the 1984 Yearbook of The Tire and Rim Association Inc. (TRA). Page XIII of the Yearbook is dedicated to New Tire Dimensions and particularly outlines Measuring Procedures for New Tires, Definition of Terms and the Method of Calculating Percent Tire Deflection. The terminology included in the Definition of Terms is either compatible or complementary to the terminology contained in ASAE S296.2, Section 4. Page XVI of the TRA Yearbook describes the approved procedure for rounding data. Briefly this procedure is shown in Appendix A, Table A.3.

The English unit system is used by the tire industry in defining tire dimensions. All the information relative to tire dimensions is presented in inches unless otherwise stated. Information concerning rim specifications will not be taken into consideration since it is beyond the scope of this study. A reasonable assumption is the compatibility of the rim with the selected tire size.

Section 4 of The TRA Yearbook refers to agricultural tires. Table A.4 is an index of the agricultural section. On page 4-02 of the TRA Yearbook the criteria for selecting tires for agricultural vehicles are listed. The definition of terms maintains either compatibility or consistency to the terms presented on page XIII of the Yearbook as well as to ASAE S296.2.

The tires that are used on tractors are coded according to their application, using a letter and a number, and according to the tire size, using the section width of an inflated new tire and the rim diameter, both expressed in inches. The tire coding scheme is presented in Table A.5. The aforementioned coding implies that the particular tires are best for a specific use.

A further step in encoding tires is the use of letters associated with the tire size, as descriptives. The two letters that are most frequently used as an extension of the section width component of the tire size are the letter L, characterizing a Low Section Height tire and the letter R, characterizing a Radial Ply tire.

The environment and particularly the soil is a factor that greatly affects the outcome of the farming operation. Several soil classification systems are in use. However, only a few can be used by engineers.

The soil is a factor with maximum variability. The most popular engineered based soil classification system is the Unified Soil Classification System (USCS, 1960) and will be followed throughout this study.

In conclusion of the terminology discussion it should be declared that hereafter all the pertinent information as well as formulae deduction with regard to tractors, tires and soil, will conform with the terminology listed herein. Moreover, the ASAE Standards-1984, the 1984 Yearbook of The Tire and Rim Association, Inc., the 1984 Handbook of the Society of Automotive Engineers and the Unified Soil Classification System will be considered as the major sources of information and terminology. If references to other sources or standards are to be made they will be stated explicitly.

Terminology with regard to Computing Science and Engineering is not presented herein. However, deviation from the standard methods of presenting information should be allowed due to the particular characteristics of this field.

## 3. FROM THE PAST TO THE FUTURE

Early attempts to use mechanical power for farming operations began around 1850 taking advantage of steam power. However, the first attempt to use steam for moving a "reaction turbine" - called aeolipile - is attributed to Hero of Alexandria and is believed to have been made circa AD 50. Since then, the pioneering work of Otto von Guericke around the year 1650 - Magdeburg hemispheres - established the theoretical model on which the contemporary engines are implemented. The work of Denis Papin in France and Thomas Newcomen in England around 1700 were the foundations of steam engine application as a power plant. Newcomen's engine was the one that gave motive power to the Industrial Revolution. Another well known contributor of the steam engine evolution was James Watt. His work on steam engines in the late eighteenth to early nineteenth century led to the foundation of the Boulton and Watt company. A significant step was the use of a reciprocating engine to produce rotary motion (Van Riemsdijk and Brown, 1980).

The use of the steam engine in agricultural traction opened new horizons in farming operations. Since then the tractor has been changed remarkably in every aspect, though maintaining some general characteristics.

In order to realize the changes the tractor has undergone due to technology evolution, the features of the early tractor should be compared to the features of the contemporary tractor. The major features of the early tractor were:

- a low output power steam engine as the power unit
- a heavy frame to accommodate and secure the boiler
- steel wheels with lugs
- low travel speed
- lack of comfort or protection for the operator
- lack of accessories for external equipment.

Each of the aforementioned features was considerably developed, resulting in the powerful modern tractor. The study of tractor evolution can reveal which of these features can be further developed and which ones have already reached a maximum level.

The first feature of the tractor that should be examined is the power unit and the associated fuel. The middle of the eighteenth century found the world in the boom of the industrial revolution. The steam engine, even though stationary, was both popular and promising. A logical consequence of this situation was that the first tractor was powered by a steam engine.

The capabilities of these early tractor power units were very limited in terms of heavy load handling. Power output was low due to the low thermal efficiency of the early steam engines. The evolution in power unit design resulted in the introduction of the internal combustion engine using fossil fuels. The new engine was operated with the Otto cycle. By the year 1919 when official tractor performance testing began at the University of Nebraska's Tractor Testing Laboratory at Lincoln, two main fuels were available - kerosene and gasoline (Larsen, 1981). Since then the internal combustion engine has become the dominant type of power unit for agricultural tractors.

The evolution of the power units followed the trends in fossil fuel use. By 1925 distillate was accepted as a replacement for kerosene since it was considered a better fuel. However, kerosene continued in use until 1934. Distillate remained a popular and economical fuel for many years and continued in use until 1956 (Larsen, 1981).

On the other hand gasoline proved the most popular fuel following World War II. Farmers liked gasoline because gasoline engines started easier than those using distillate, the dilution in the crankcase oil was less and there was the advantage of stocking only one fuel on the farm. Another advantage of the gasoline engine was the higher compression ratio - 7:1 - compared to the distillate-burning engine, which had a compression ratio of 4.7:1. The result was that gasoline engines with the same displacement (bore and stroke) as distillate-burning engines developed more power. A new fuel introduced in 1949 for use in agricultural tractors was Liquified Petroleum Gas (LPG), primarily propane. LPG-burning engines also had a compression ratio of about 8:1 but the result in terms of output power was not significantly different from gasoline (Larsen, 1981).

A significant change in power units was the introduction of diesel engines in 1932. The first diesel tractor tested at Nebraska was a Caterpillar. Since then the trend in using diesel as tractor fuel has steadily increased (Larsen, 1981). The ascending course of the diesel engine in terms of popularity began in the early 1960's. At approximately the same time the countdown for gasoline and LPG engines began. In the early 1970's tractors with LPG engines were no longer being submitted for testing at Nebraska. At the same time gasoline engines lost their popularity and diesel became the dominant tractor fuel..

The reasons for diesel popularity were the following:

a. much higher compression ratio - 14:1 minimum, 22:1 maximum - resulting in higher output power
b. the cost of diesel fuel production was less compared to gasoline and LPG, resulting in lower price per unit volume
c. lower fuel consumption
d. less engine maintenance, therefore less operating cost.

The conditions that made the diesel engine viable were:

a. increased durability of the engine alloys to withstand the higher pressures
b. an improved system of fuel injection in the cylinders.

Of course not only the improvement of tractor engine design caused the improvement of the tractor performance. Factors like increased rated engine speed and compression ratios, use of turbochargers and intercoolers and improved power trains and final drives boosted the power developed both at the engine and at the drawbar. However, due to limited fossil fuel resources the following alternatives should be considered in the near future:

a. use of alternative fuels for the engines, like methanol, ethanol and other carbohydrates, hydrogen or ammonia (Canadian Alternate Fuels, 1983), or use of vegetable oils, like Canola or Rapeseed oil (Strayer and Craig, 1983)

b. use of electrical power units, like Allis-Chalmers' fuel cell (fc) experimental tractor. The 1008 individual fuel cells with 1 V/fc provided 15 kW of total electrical output. The fuel gas in use was a mixture, largely propane (Larsen, 1981).

As far as combustion engine design is concerned, no radical changes can be foreseen. Therefore, the power unit has reached a level of maturity and only minor improvements in minimizing power losses should be expected. Of course that does not imply that a revolutionary design is impossible.

Another feature of the early tractors was the heavy construction of the frame, as a result of the bulk of the system producing the steam. Also the use of steel for every part of the tractor increased the gross weight remarkably. Since the output power was very low the result was that the tractor weight per unit power (kg/kW) had a negative influence. Also, the tractive efficiency was low, even though the tractor was heavily ballasted for traveling at low speeds (Domier and Willans, 1978). The low tractive efficiency was due to excessive motion resistance.

With the introduction of the internal combustion engine and improvement of the tractor design, the available power increased whereas the tractor weight per unit of output power developed decreased. This change resulted in an increase in travel speed due to a reduction in motion resistance. However, this was not significant until the middle of the 1930's when pneumatic rubber tires with lugs replaced the steel wheels. Currently, the tractor weight has been reduced considerably to the point that most of the time added weight (ballast) is required to increase drawbar pull and tractive efficiency. New alloys, the use of plastic and improved designs have contributed significantly to tractor weight reduction. Domier and Willans (1978) recommended a 60 kg/kW weight to power ratio for a two-wheel drive tractor. The contemporary tractor requires extra weight to obtain this figure, therefore, there is no practical reason for making a more lightweight tractor. Now the important aspect of tractor weighting is the distribution of the weight between front and rear axle. Two-Wheel drive (2WD), Four-Wheel drive (4WD) and Front Wheel Assist (FWA) tractors have different weight distribution requirements, regardless of the tractor weight.

In early 1934, the University of Nebraska Tractor Test Board offered to conduct drawbar tests on pneumatic rubber tires for no additional fee over the usual steel wheel tests. The first rubber tired tractor tested was an Allis-Chalmers WC. The improvement in performance was remarkable when pneumatic rubber tractor tires were used during the test. During the two economy runs the power developed showed over a 25% increase at the same engine speed and almost the same load. Fuel economy was also improved over 25% (Larsen, 1981).

Undoubtedly the use of rubber tires on tractors was a milestone in the development of agricultural tractors.

Firestone working with Allis-Chalmers, GOODYEAR with Case and later BFGoodrich with US Rubber, started experimenting on agricultural tractors. Today all three companies - Firestone, GOODYEAR, BFGoodrich - are some of the biggest names in the tire industry.

The first tractors were not propelled faster than a horse pulling an implement. Until about 1900 the maximum tractor travel speed was approximately 4 km/h. After 1900 and until 1936 the tractor travel speed increased very little. After the introduction of pneumatic tires the travel speeds increased about five fold. The modern tractor can travel as fast as 35 km/h.

The new power transmissions developed by the tractor companies contributed significantly in both torque and wheel speed increase, using a wide range of transmission ratios. The first steam engines drove the wheels directly without interference of a transmission. The introduction of transmissions for speed and torque selection considerably increased the efficiency of the tractor.

The early transmissions were mechanical trains of gears to transfer the engine power to the drive wheels. Mechanical transmissions are of three major types:

a. Sliding gear
b. Collar shift
c. Synchromesh.

An advance to mechanical transmissions was the introduction of the hydraulic assist transmissions. In this type of transmission the gear was coupled with hydraulic clutches, controlling the power flow "on the go". At the same time, planetary gears were introduced.

The latest advances in transmissions are:

a. Hydrostatic transmissions
b. Hydrodynamic transmissions (Torque converters).

The characteristic of hydrostatic transmissions is the use of fluids at high pressures and relatively low velocities. Energy is transferred in a closed circuit between a positive displacement pump driven by the engine and a positive displacement motor.

The torque converter is an automatic fluid drive that transmits engine torque by means of hydraulic forces, shifting smoothly through an infinite number of speeds. The torque converters, driven by fluids at low pressures and high velocities, are the opposite of hydrostatic transmissions. The converter section is coupled with a range gear section followed by a final drive section.

A part of the power train that contributed significantly in tractor performance improvement is the differential. The most important feature of the differential is that each drive wheel is allowed to rotate at a different speed and still carry its own load. Additionally, the differential can be locked so as to not allow independent operation of the wheels mounted on the same axle. There are three types of differential locks:

a. Mechanical
b. Hydraulic
c. Automatic (No-Spin).

There is considerable progress in power train design, however, more work can be done. Conventional transmissions offer a significant combination of gears. However, the losses of power in the transmission many times become significant, resulting in reduced power delivery to the driving axle.

An immediate result of the travel speed increase, besides the increase in field capacity, was an increase in drawbar power under the same pull developed by the tractor.

The last feature of the early tractors concerned operator comfort and safety as well as lack of accessories. In these areas no advances were observed till the 1960's. During the 1920's and 1930's the pressed steel pan seat was standard equipment for most farm tractors and the operator was completely exposed to the dangers of roll-over as well as to the adverse weather conditions. In the early 1960's John Deere introduced human factor engineering and in the middle of the decade the same company promoted Roll-Over Protective Structures (ROPS).

Currently both operator comfort and safety are primary concerns of tractor manufacturing companies. Both issues have become so important that entire departments of tractor companies are dedicated to safety and comfort research. Also, both issues are included in the ASAE standardization code, which deals with the following:

1. Safety
    - Roll-Over protective drivers cab
    - Protection of other vehicles from long agricultural implements transported on the highway
    - Operator protection from moving parts (e.g. PTO).
2. Comfort
    - Noise protection
    - Operator protection from adverse weather conditions
    - Operator protection from dust
    - Operator protection against tractor vibration

Signs and warning lights providing ease of operation.

As far as accessories is concerned, early tractors were equipped with a pulley for transmitting power to an external implement. The PTO gradually replaced the pulley for power transmission to an implement. The use of clutches enabled independent operation of the PTO, thus becoming a very handy tool for the tractor. The use of hydraulics gave birth to many applications, such as hydraulic three-point hitch for mounted implements, power steering, hydraulic brakes, etc. Hydraulic couplers enabled the transfer of hydraulic power to the implement. Electronics enabled operator's control of the tractor "at the fingertip".

In conclusion the contemporary tractor is far ahead in terms of appearance and capabilities from the early tractor. Göhlich (1984) presented a review of the development of tractors and other agricultural vehicles, emphasizing the optimization of power use, implement mounting, power transmission mechanisms and operator comfort. It is Göhlich's opinion that the emphasis in tractor development will be concentrated on reducing the total weight of the tractor-implement system in order to minimize ground pressure and soil compaction. Also, the concept of the front mounted implement was referenced. Both use of electronics and operator comfort are seen as important areas of future tractor research.

However, there is one more step that the tractor has to take. That is to become an "intelligent" tool. A step towards this direction is the use of microelectronics and state-of-the-art sensors and actuators. Searcy and Ahrens (1983) presented an idea of how microcomputer technology can affect tractor monitor and control. Hendrick et al (1981), Shropshire et al (1983) and McKinion (1984) among other researchers presented applications of microprocessors on tractor monitoring and control. Chancellor and Thai(1983), Young et al (1983) and Smith (1984) presented studies on automatic control of various functions of the tractor, like the engine speed, the steering and the transmission.

A tractor-environment feedback process and control will be required to complete the idea. The major problem in providing the tractor the ability to monitor tractor-environment interaction is the absence of established knowledge in this area due to the variability and unpredictability of the environment. The development of computer simulation models strives for a realistic solution of this problem. On the other hand, the use of microcomputers on the tractor will enable the understanding and the efficient control of the system.

# 4. LITERATURE REVIEW

Studying tractor performance in-the-field is necessary to investigate the role of three major factors as well as the mechanisms through which these factors affect tractor performance. The three factors are,

a. the soil
b. the traction device
c. the tractor design

The abovementioned factors constitute the three major dimensions that determine tractor performance and they are characterized by multiple inter-relationships.

In order to analyze each factor and its contributing role in determining tractor performance, a logical differentiation of the subjects was necessary. The description of each factor includes a brief terminology, when applicable, the properties of each particular factor and the mechanisms through which tractor performance is affected. Finally, the inter-relationships among the three factors are presented.

The literature review is structuraly divided into three sections relevant to soil, traction devices and tractor design. This division into subjects was decided for better subject presentation.

## 4.1. Soil and its properties

The soil is the medium of farming operation. Moreover, soil is the factor that most greatly affects tractor performance through its variability and unpredictability.

*Soil* from an engineering standpoint is the loose agglomerate of mineral and organic materials and sediments found above the bedrock (Holtz and Kovacs, 1981). The agricultural soils are examined from different optical corners, depending on their use. From the Plant Science viewpoint the soil is the medium for the planting operation. From the Power and Machinery viewpoint soil is the terrain for off-the-road machinery.

The increasing production of diverse off-the-road vehicles has generated a greater interest in the theoretical study of the principles involved in off-the-road locomotion. This study may be called *terramechanics*. The off-the-road locomotion encompasses the *terrain evaluation* and *trafficability studies* (Reece, 1964). Knight and Freitag (1962) define trafficability studies as the vehicle mobility on any terrain. To be adequate for a vehicle, a soil must have sufficient bearing capacity to prevent the vehicle from sinking too deeply and sufficient traction capacity to provide the necessary forward thrust of the vehicle's wheels or tracks. Both bearing capacity and traction capacity are functions of soil strength and it is not possible to separate the two effects.

The study of the soil behavior inevitably is relevant to the study of the physical and mechanical properties of the soil, especially when the soil is considered as a deformable body. In this aspect agricultural engineering is related to geotechnical engineering. The most important aspect of geotechnical engineering, relevant to agricultural engineering, is *soil mechanics* which describes the mechanics and properties of the soil (Holtz and Kovacs, 1981).

### 4.1.1. What is soil?

*Soil is a heterogeneous, nonlinear, nonconservative and anisotropic material.* The soil is heterogeneous due to its variability, nonlinear due to the form of the stress-strain curve, nonconservative due to the ability to remember changes occurred in the past and anisotropic due to differences in behavior along different directions. (Holtz and Kovacs, 1981).

Although the study of soil from an engineering viewpoint seems to be well defined, it is largely based on empiricism, case study and "educated guess" due to soil variability. Most current theories that are trying to predict and explain soil behavior are based on assumptions like soil homogeneity or linearity. In some cases these assumptions may be valid, however, in general terms they are approximations. The necessity of predicting and describing soil mechanical behavior led researchers to develop methods for measuring and classifying the soil according to certain physical properties like strength, granular distribution etc. The apparent properties of soil are due to soil structure, texture and quality of constituents.

### 4.1.2. Structure, texture and soil constituents

In geotechnical engineering practice, the term soil *structure* describes both the geometric arrangement of the particles or mineral grains as well as the interparticle forces which may act between them. A term relevant to structure, is soil *fabric*, which refers only to the geometrical arrangement of the particles. The agricultural soils are fine-grained cohesive soils, in which the interparticle forces are relatively large. Therefore, both the interparticle forces and the fabric of these soils must be included in the soil structure. Knowledge of both soil properties is required to completely describe the soil. The structure strongly affects or governs the engineering behavior of a particular soil. Most studies on cohesive soil structures describe only the soil fabric. From the fabric certain inferences are made about the interparticle forces. Soil behavior in engineering practice is strongly influenced by the *macrostructure* of the soil, including the stratigraphy of fine-grained soil deposits. The *microstructure* is more important from a fundamental than an engineering viewpoint, although the understanding of the microstructure aids in general understanding of soil behavior (Holtz and Kovacs, 1981).

The soil *texture* is its appearance or "feel", and depends on the relative sizes and shapes of the particles, as well as the range of distribution of those sizes. Basically the soil can be classified as coarse-textured (coarse-grained) or fine-textured (fine-grained). For fine-grained soils the presence of water greatly affects their engineering response and particularly their *plasticity* and their *cohesiveness*. The grain size distribution of a soil will be examined along with the presentation of the soil classification systems (Holtz and Kovacs, 1981).

As far as the constituents of agricultural soils is concerned, the term *clay* must be defined. In civil engineering, clay means a soil which contains some clay minerals as well as other mineral constituents, has plasticity, is cohesive and dilatant (soil behavior is affected by the water content). The most important clay minerals in clay soils are *Kaolinite*, *Montmorillonite*, *Illite* and *Chlorite* (Holtz and Kovacs, 1981).

### 4.1.3. Soil classification

The soil classification for engineering purposes is primarily based on the grain size distribution and the mechanical differences attributed to the structure of the soil.

The grain size distribution is plotted as percentage of grain finer than a specific grain diameter versus the logarithm of the grain diameter, expressed in millimetres. The particle size distribution is obtained through a process called *mechanical analysis* or *gradation test* (Holtz and Kovacs, 1981).

Four widely known soil classification systems have been introduced by, a) the American Society for Testing and Materials (ASTM, 1980), b) the American Association for State Highway and Transportation Officials (AASHTO, 1978), c) the U.S. Army Engineer Waterways Experiment Station (1960) and the U.S. Bureau of Reclamation (1974), titled Unified Soil Classification System (USCS) and d) the Massachusetts Institute of Technology (Taylor, 1948). The most commonly used soil classification system for engineering purposes, including agricultural engineering, is the Unified Soil Classification System (Holtz and Kovacs, 1981).

The Unified Soil Classification System was originally developed by Professor A. Casagrande (1948) for use in airfield construction during World War Two. The system was modified in 1952 by Professor Casagrande, the US Bureau of Reclamation, and the US Army Corps of Engineers to make it suitable for other applications. The USCS is briefly described in Table A.6, (Holtz and Kovacs, 1981).

The grain size distribution according to USCS is determined from two numbers,

i. Soil Fraction or Component

ii. Coefficient of Uniformity ($C_u$) of the soil.

$$C_u=D_{60}/D_{10} \qquad 4.1$$

where: $D_{60}$=grain diameter (mm) corresponding to 60% passing

$D_{10}$=grain diameter (mm) corresponding to 10% passing

The US Army Engineer Waterways Experiment Station (WES) uses this system of soil classification to report results of tests for evaluation of the in-soil performance of tires (Turnage, 1976).

Another soil classification system suitable for trafficability studies is the one introduced by the American Association of State Highway and Transportation Officials (Holtz and Kovacs, 1981).

### 4.1.4. Theory of soil compaction

*Compaction* is the densification of soils by the application of mechanical energy. It may also involve a modification of the water content as well as the gradation of the soil (Holtz and Kovacs, 1981).

In civil engineering, and especially in foundation and transportation aspects, soil compaction is a common practice. In agricultural engineering, as far as soil trafficability is concerned, compaction is desirable to improve tractor performance due to decreased slip and motion resistance. However, from a purely agricultural viewpoint, soil compaction is detrimental, therefore, soil compaction by the tractor should be minimized. Off-highway vehicles interact with soil at high rates of strain, resulting in strain failure (deformations). This has resulted in a special body of scientific activity and knowledge referred to as Soil Dynamics (Wismer, 1982).

Earlier in the chapter the effect of the traction members on soil stress and strain was referenced. Wood and Wells (1984) presented a study with regard to the effects of unpowered and powered wheels on a combined stress-strain compaction model. Soil deformation versus depth was measured. The theoretical approach of the study was directed at the combination of the Froehlich-Boussinesq soil pressure distribution equation with the log-linear relationship between bulk density and applied stress, as modified by Amir et al (1976), to include the effect of soil moisture content. The experiments were conducted in the University of Kentucky soil bin. The results as far as stress-strain relationship is concerned, were in agreement with compaction theory and the Standard Proctor test results. Change in volume due to soil deformation, resulting from wheel traffic, was termed as coefficient of deformation ($C_d$), and was defined as a function of initial and final porosity of a soil element. Most of the soil compaction models relate the volume change in soil (porosity) to applied stress.

The Froehlich-Boussinesq equation is the following:

$$\sigma=(\nu Q/2\pi z^2)\cos^{(\nu+2)}\phi \qquad 4.2$$

where $\sigma$ is the vertical compressive stress at a specific point in the soil mass, $\nu$ is the Froehlich concentration factor, z and $\phi$ are the polar coordinates of the point in question and Q is the point load on the surface contact area.

The Froehlich concentration factor $\nu$ in the Froehlich-Boussinesq equation varies from four (hard, dry soil) to six (wet soil) and describes the increase of the iso-pressure line concentration about the load axis beneath the tire track.

Bowen et al (1984) presented a computer model for determining the vertical stress distribution in the subsoil, resulting from a combination of point and distributed loads applied to a tire print shape using Boussinesq's equation. Summarizing their experiences, the authors pointed out the merits of the program for educational purposes.

Nichols et al (1984) developed a stress state transducer for soil, that measured normal pressures in six predetermined directions, to provide data for mathematically determining the complete stress state within a finite soil region. The mathematics for defining the state of stress at a point, were based on the calculation of the three independent normal stresses ($S_{xx}$, $S_{yy}$, and $S_{zz}$) and the three independent shearing stresses ($S_{xy}$, $S_{xz}$, and $S_{yz}$) applied on a unit volume cube at equilibrium. A strain gage was selected as the sensing element, due to geometrical considerations and stress rate of change.

Kline and Perumpral (1984) presented a computer model for predicting the vertical stress distribution resulting from uniformly-distributed loads over circular and elliptical areas. The computer model was based on the Froehlich-Boussinesq equation, using finite element analysis, integrating the equation

$$dQ_n = p * dA_n \quad \text{.......................................} \quad 4.3$$

where $dQ_n$ is an equivalent point load as the result of a pressure p applied on a finite area $dA_n$. The effect of contact area change, applied dynamic load change, geometrical differences (circular versus elliptical contact area), and the Froehlich concentration factor change, were investigated. The ability to use an axi-symmetric model (two-dimensional) instead of a three-dimensional model in performing finite element analysis, was very valuable.

Carpenter and Fausey (1983) presented a study concerning the role of the tire size as a function of load, for minimizing subsoil compaction. The objectives of the study were, a) the determination of the effects of weight, weight distribution and tractive characteristics upon pressure distribution in the subsoil; b) the formulation of a graphical model to describe pressure distribution in the subsoil under tractor tires and c) the development of a tire design or configurations, which would result in reduced compaction while maintaining or improving the tractive efficiency. In conducting the study, the interrelationships between soil pressure, soil types, soil moisture and soil compaction were considered. The researchers used the formula

$\sigma=Q(1-\cos^{\nu}\theta)$ ....................................4.4

presented by Froehlich, for predicting soil compressive stresses. The angle $\theta$ represents one half the angle of a circular cone whose vortex is at the point of stress. The values of the concentration factor $\nu$, varied from 3 to 6. The design implications of this study show that the surface pressures should not exceed 100 kPa and for this purpose the most suitable configuration is tandem wheel arrangements with second choice being a dual tire configuration. The researchers concluded that the solution to subsoil compaction is either the further pressure reduction of the pneumatic tires or the application of controlled traffic type operations.

Campbell and Dickson (1984) presented a comparison of four front tires with respect to soil compaction, using a rear wheel designed to minimize compaction. A conventional cross-ply, a wide section cross-ply, a wide section radial and a very wide section low pressure tire were tested. In conclusion the wide section radial and the very wide section tires produced appreciably smaller increases in soil bulk density than the other two tires, when front-end weight was used. Without front-end weight insignificant differences were observed implying that unnecessary front-end weight should be avoided.

Minimizing compaction of agricultural soils was the primary reason for introducing the concept of prepared traffic lanes or "controlled traffic" farming. The interest in "controlled traffic" increased along with increasing tractor power and weight.

Morling (1982) presented the concept of "controlled traffic" as the operation of all load bearing wheels and tractive energy wheels on specific limited width compacted traffic paths within the crop area. According to this study "controlled traffic" has advantages and disadvantages, as opposed to the conventional random operation of crop production equipment. The advantages referred to the crop growth, yield and timeliness, the soil preservation, the tractor performance, the tillage system, the farming economical considerations and machinery standardization. More specifically in tractor performance, better tractive efficiency of powered wheels, less motion resistance of unpowered wheels, use of smaller wheels and tires (less flotation required), terrace action on side slopes (raised paths) and better timeliness for planting and harvesting operations were referenced. The disadvantages relevant to machinery are, the need for specific traffic paths that must be followed at all times, matching of all the equipment in hand with the path spacing and the need for an automatic guidance system to maintain path location. Additional disadvantages relative to crop production were also referenced.

A very interesting point made in this study is the recognition of the inversely proportional relationship of the soil compaction and the moisture stress condition. Soil compaction is beneficial under low soil moisture content. In terms of soil condition the "controlled traffic" was found to be beneficial, preserving soil structure as well as water and air permeability. Compacted soils need many years to recover their structure.

Burt et al (1984a) working on the traction characteristics of prepared traffic lanes, attempted a comparison of pneumatic tire performance operating on prepared traffic lanes and on simulated seedbed condition for selected soil types and soil moisture conditions. Net traction and tractive efficiency of the tires as well as the time delay following a flooded soil condition for adequate mobility on prepared traffic lanes and on the simulated seedbed were determined. All the tests were conducted using the National Tillage Machinery Laboratory single wheel agricultural tire test machine. A wheel with lugs was tested against a smooth tread wheel. Generally the traffic lanes showed to be more beneficial as the terrain trafficability decreased due to increased soil moisture content. The gain in timeliness was up to two days in favor of the traffic lanes.

The common conclusion of the aforementioned studies was that the advantages of the "controlled traffic" are more than the disadvantages, even though some technical adjustments are required.

Soil compaction is closely related to the grain size distribution, the density of the soil solids $\rho_s$ and the moisture content of the soil. The more fine-grained and well-graded the soil is, the higher the dry density $\rho_d$ of the soil after compaction, for the same moisture content. Inversely, the soil compaction increases along with moisture content until a maximum will be attained (Holtz and Kovacs, 1981).

Wells and Burt (1984) presented a study with regard to bulk density and cone penetration resistance of disturbed soils due to powered pneumatic tire traffic. Two soil types at various moisture conditions were used during the tests. Dual probe nuclear gage bulk density measurements were compared to gravimetric core samples. The soil bulk density was measured below and beside tire footprints. Generally, gravimetric and nuclear gage methods for determining moisture content and dry bulk density gave significantly different results. The study was conducted at the National Tillage Machinery Laboratory, Auburn, AL. and was parallel to an aforementioned study presented by Burt et al (1984).

Cromer and McLendon (1984), motivated by the need for efficient water management, presented a microprocessor-based radio telemetry system for determination of soil moisture content.

A standard laboratory compaction test is the *Proctor test*, measuring soil *compactive effort* due to *dynamic* or *impact compaction*. The resultant curve from the Proctor test determines soil compaction *dry of optimum, near or at optimum* and *wet of optimum* (Holtz and Kovacs, 1981).

Raghavan and McKyes (1977b) conducted a laboratory study to determine the effect of slip-generated shear on soil compaction, using a shear box. The conclusions of this study were that maximum soil compaction occurs for slip values between 10 and 30% and that the combined effect of normal stress and shear stress causes the same soil compaction as twice the normal stress alone.

Johnson et al (1983) studied the compactability of soils produced from the mixing of the topsoil with the subsoil, due to farming operations. Using a triaxial test apparatus and the Proctor test, they measured volumetric strain versus hydrostatic stress and maximum density of the topsoil, the subsoil and the mixture. An empirical equation was derived, describing soil deformation as a function of hydrostatic stress and particle size distribution. The percentage of sand and the liquid limit of the soil affected the Proctor density.

Gameda et al (1984) attempted to correlate predicted soil stress as defined from models based on the elastic theory and actual bulk density profiles in soils subjected to compactive loads in order to investigate the degree of soil compaction induced by large agricultural vehicles. The amount of load, the size of contact area between tire and soil, the distribution of contact pressure within this area, and the texture, moisture content and bulk density of the soil was taken into consideration.

Johnson et al (1984) developed a mathematical model of soil compaction, using a method of predicting soil bulk density caused by repeated hydrostatic loading, in an attempt to simulate the effect from multiple passes of a pneumatic tire over a terrain. The soil volume change hysterisis curve was measured under repeated loading and unloading. Moreover, the natural volumetric strain versus the hydrostatic stress was measured.

The analysis of the stress-paths is of major concern for the researchers dealing with soil dynamics, since it severely affects soil behavior (Holtz and Kovacs, 1981).

Timeliness and tractor go or no-go conditions probably can be determined by the compaction-water content relationship.

### 4.1.5. Soil strength and failure theories

An important property of the soil is the stress-strain relationship. In defining soil attributes it has already been said that the soil is nonlinear. Moreover the stress-strain relationship is independent of time.

By defining *strength* of a material based on the stress-strain relationship, it can be said that this is the maximum or yield stress, in other words the stress at some strain which has been defined as *failure*. To define failure of the material there are many *failure criteria*, among which the most important is the *Mohr-Coulomb failure criterion* (Holtz and Kovacs, 1981).

Around the turn of this century Mohr (1900) hypothesized a criterion of failure for real materials in which he stated that materials fail when the *shear stress on the failure plane at failure reaches some unique function of the normal stress on that plane*, or

$\tau_{ff}=f(\sigma_{ff})$ ........................................4.5

where $\tau$ is the shear stress and $\sigma$ the normal stress. The first f refers to the *failure plane*, whereas the second f means *at failure*. The $\tau_{ff}$ is called *shear strength* of the material and is a very important property of the soil (Holtz and Kovacs, 1981).

Long before the Mohr failure criterion, Monsieur Dr. Coulomb (1776) was employed with military defence works, such as revetments and fortress walls. Coulomb trying to solve the problem of lateral pressures exerted against retaining walls devised an equation involving stress, cohesion (c) and angle of internal friction ($\phi$) of the soil. The Coulomb's equation is,

$\tau_f=\sigma \tan\phi + c$ ........................................4.6

where $\tau_f$ is shear strength of the soil, $\sigma$ is the applied normal stress and $\phi$ and c are called *strength parameters* of the soil, as defined above.

The combination of the two aforementioned approaches gave birth to the *Mohr-Coulomb strength criterion*. The

Mohr-Coulomb criterion is by far the most popular strength criterion applied to soils and can be written as,

$$\tau_{ff} = \sigma_{ff} \tan\phi + c \qquad 4.7$$

The aforementioned equation determines the Mohr failure envelope of the soil, in other words a set of shear stress-normal stress values, which define whether a material can fail or not. The Mohr failure envelop refers to "at failure" (Holtz and Kovacs, 1981).

Micklethwait (1944) applied a modified Coulomb equation to track vehicles, defining maximum tractive effort. Bekker (1956) further modified this equation making it applicable to wheels as well as tracks, and accounting for wheel/track slip and soil stress-strain relationship. The original equation has been revised by many researchers over the past two decades. The original and the revised Bekker model computes net traction as the difference between gross traction (thrust) predicted from the ring shear test and motion resistance predicted from the plate penetration test, developed by Bernstein (1913). Bekker extended Bernstein's relationship and Reece (1964) suggested a modified version of the Bekker compaction resistance equation. Description of the tractor parameter equations and the referenced tests, as summarized by Wismer (1982), will be given in the appropriate sections.

McKibben (1938) attempted to relate transport wheel geometry, slippage and a simple measure of soil penetration resistance, using rigid steel wheels and impact penetrometer readings. McKibben found that the rolling resistance of steel wheels varied approximately from 0.6 to 1.3 power of load, the -0.5 to -0.7 power of diameter and the -0.5 to 0.5 power of the width. Models describing soil-implement interaction were developed and dimensionless numbers representing the gravitational, cohesive and adhesive components of the soil reaction were calculated.

Yong et al (1976, 1977, 1978), Perumpral and Desai (1979) and other researchers, have applied the finite element method to the strain and displacement states of soil-machine systems. If the finite element method is proven successful it may make generalized soil machine models possible for all off-road machinery. It also may contribute to the rationalization and measurement of soil properties significant to soil-machine systems.

### 4.1.6. Measuring soil properties

#### 4.1.6.1. Soil strength

The most commonly used tests for determining soil strength are divided into *in situ* tests and laboratory tests. Both types will be briefly described. Some of the tests are rather complicated and for further details consultation of manuals and books on laboratory testing is recommended, especially those by the ASTM (1980), U.S. Army Corps of Engineers (1970), U.S. Bureau of Reclamation (1974) and Bishop and Henkel (1962).

A well known laboratory test for defining soil strength is the plate penetration test, based on the original concept of Bernstein (1913) who related the resistance of soil to penetration by a plate or probe, as

$p=k * z^n$ ........................................4.8

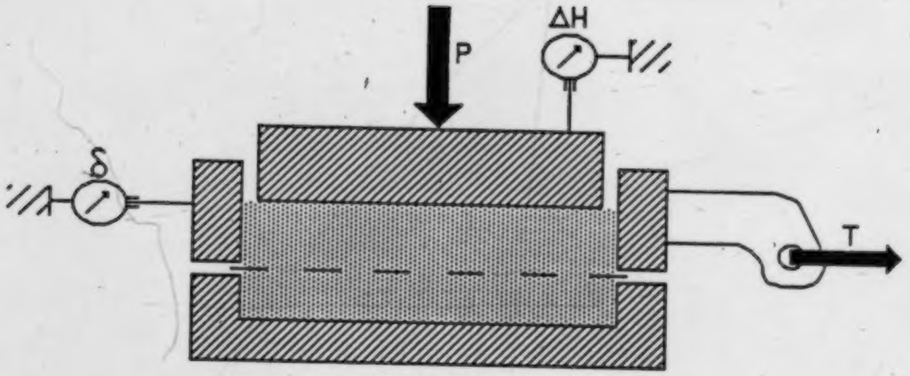
where p was the resistance of soil to penetration of a given plate or probe at any depth z. The constants k and n were fitting parameters related to soil properties and the geometry of the plate (Wismer, 1982).

Holtz and Kovacs (1981) refer to the following soil strength tests as the most popular laboratory tests.

a. Direct Shear Test (DST)

This is probably the oldest test. The test in principle is quite simple, consisting of a specimen container, "shear box", separated horizontally into two halves. The one-half is either pushed or pulled horizontally with respect to the fixed half. Figure 4.1 shows the Direct Shear Test apparatus.

A normal load is applied to the soil specimen in the shear box through a rigid loading cap. Shear load, horizontal deformation and vertical deformation are measured during the test. Dividing shear force and normal force by the nominal area of the specimen, shear stress and normal stress can be obtained. The failure plane with this apparatus is *forced* to be horizontal.



P : Vertical Force
ΔH : Vertical strain
T : Horizontal Force
δ : Horizontal strain

Figure 4.1. Direct Shear Test Apparatus

(Holtz and Kovacs, 1981)

The advantages of the DST are that the test is inexpensive, fast and simple, especially for granular materials. The disadvantages of the DST include the problem of controlling drainage, especially for fine-grained soil; uncertainty whether the horizontal failure plane is the weakest direction; serious stress concentration at the sample boundaries, leading to highly nonuniform stress conditions within the specimen and finally an uncontrolled rotation of principal planes and stresses occurring between the start of the test and failure.

Volfson (1983) using specially designed shear test apparatuses made an attempt to simulate the soil shear stress produced by a wheel with lugs. Four direct shear test and one ring shear test apparatuses were tested. The Mohr-Coulomb envelops were determined as a function of soil Cone Index. In conclusion the measured angle of internal friction remained fairly constant, whereas the soil cohesion varied with the geometry of the apparatus used to determine it. The results implied that the cohesion and the angle of internal friction are soil-tire interface parameters rather than soil properties.

### b. Triaxial Test (TT)

The Triaxial Test was developed about 1930 by A. Casagrande while at M.I.T. The TT comprises the development of a cylindrical compression test in an attempt to overcome some of the serious disadvantages of the DST. Figure 4.2 shows the Triaxial Test apparatus.

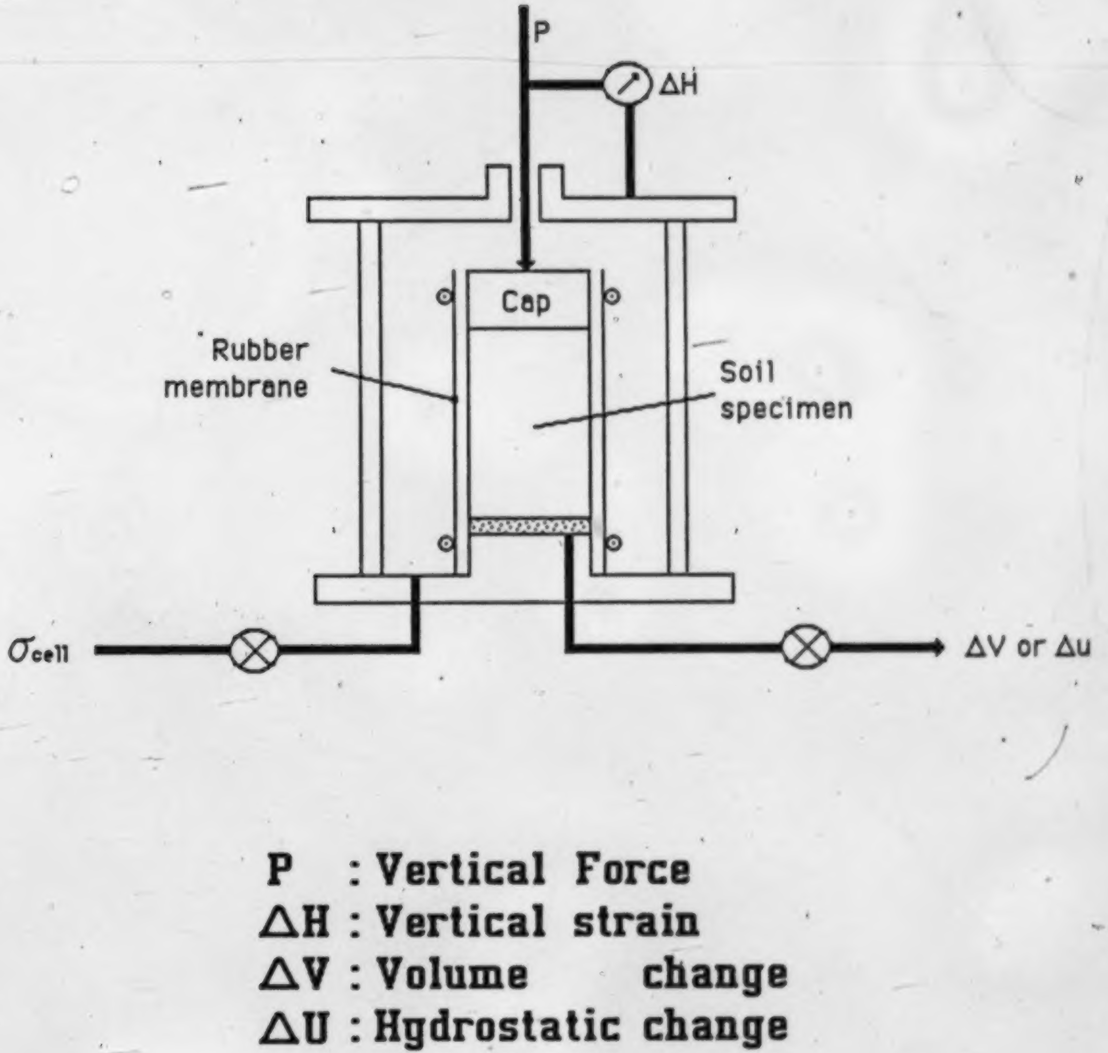

P
ΔH
Cap
Rubber membrane
Soil specimen
σcell
ΔV or Δu
P : Vertical Force
ΔH : Vertical strain
ΔV : Volume change
ΔU : Hydrostatic change

Figure 4.2. Triaxial Test Apparatus

(Holtz and Kovacs, 1981)

The TT is much more complicated than the DST but also much more versatile. Drainage can be controlled quite well and there is no rotation of the principal planes. Stress concentrations still exist, but they are significantly less than in the DST. Moreover, the failure plane can occur in any direction. An added advantage is the reasonably adequate control over the stress paths to failure. This means that complex stress paths in the field can be modeled more effectively in the laboratory with the TT. The stresses applied during the triaxial test are principal stresses.

During a TT an axial load is applied on the specimen through a piston. What is measured is volume change of the specimen during a drained test or induced pore water pressure during an undrained test.

c. other special laboratory tests are the following:

- Hollow Cylindrical Test
- Plane Strain Test
- True Triaxial or Cuboidal Shear Test
- Torsional or Ring Shear Test
- Direct Simple Shear Test

Field tests for determining the soil strength or compaction can be either *destructive* or *nondestructive*. In agricultural engineering the in-the-field soil strength is usually measured by the Cone penetrometer to obtain the soil Cone Index.

The Torsional or Ring Shear Test has been developed so that the test specimen may be sheared to very large deformations. This approach is sometimes necessary to obtain the *residual or ultimate shear strength* of certain materials. The geometrical characteristics of the ring shear apparatus are shown in Figures 4.3 and 4.4

d. other popular *in situ* tests are the following:

- annular grouser plate
- torsional shearhead
- Sheargraph
- Desometer

The Desometer was designed and built by Taylor (Dunlap et al, 1966) at the USDA National Tillage Machinery Laboratory, Auburn, AL., and is a device that applies a constant normal load to an annulus while the annulus turns at a constant speed.

Bailey and Weber (1965) presented a comparison of methods of measuring soil shear strength using artificial soils. The five devices tested were a triaxial cell, an annular grouser plate, the same annular grouser plate with enclosed outer perimeter, a torsional shearhead and the commercially available Sheargraph. Only the triaxial apparatus was a laboratory test and required a soil sample. The Cone penetrometer and the shear vane were omitted because they did not lend themselves well to operation in the shallow laboratory soil bin that was used in the study. The two artificial media used were mixtures of soil and oil. Summarizing, the measurements of shear strength using the Sheargraph were in agreement with the results from the

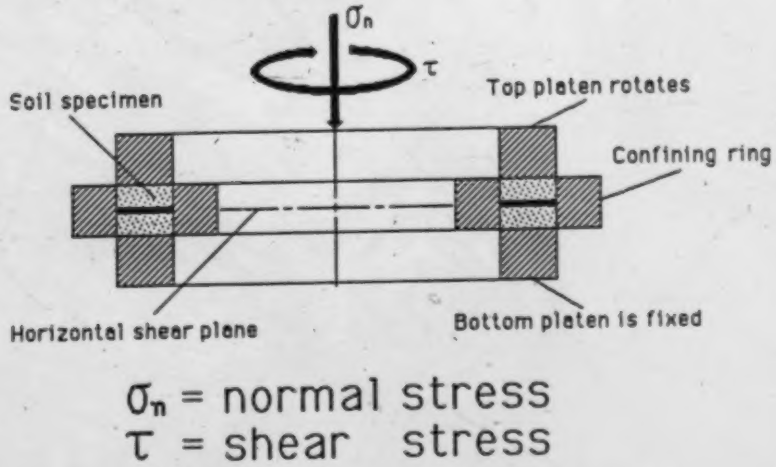

σn
τ
Soil specimen
Top platen rotates
Confining ring
Horizontal shear plane
Bottom platen is fixed
σn = normal stress
τ = shear stress

Figure 4.3. Torsional or Ring Shear Test Apparatus

(Holtz and Kovacs, 1981)

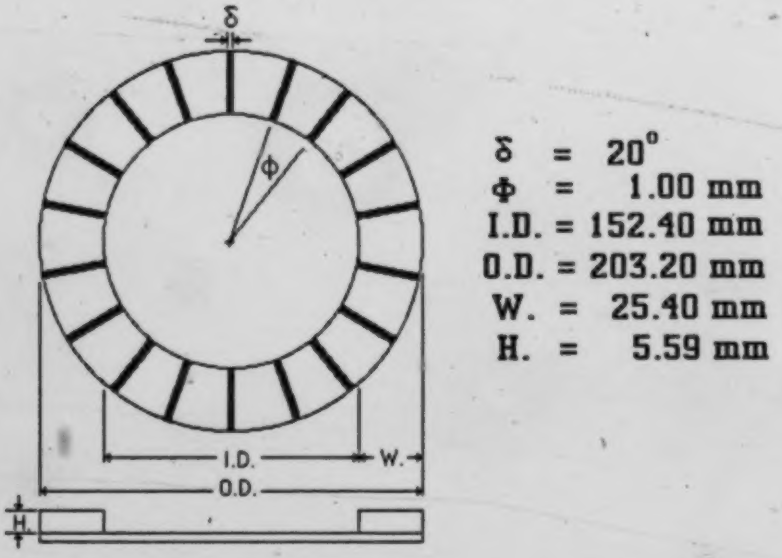

δ
ϕ
δ = 20°
Φ = 1.00 mm
I.D. = 152.40 mm
O.D. = 203.20 mm
W. = 25.40 mm
H. = 5.59 mm
I.D.
W.
O.D.
H.

Figure 4.4. Geometry of the Torsional or

Ring Shear Test Apparatus (Volfson, 1983) torsional shearhead, whereas the strength values indicated by the torsional shearhead were always higher than those from the annuli. Differences in the results among the various devices were indicated for the two soils.

Dunlap et al (1966) compared the *in situ* soil shear values obtained with devices of different geometrical shapes. The apparatuses tested were a Desometer, five different grousered annuli with varied diameters and widths, a NIAE shear box, a Sheargraph and a Cone penetrometer. All the tests were conducted in the circular soil bin at the National Tillage Machinery Laboratory. The conclusions drawn from this study were based on the different soil strength parameters measured by the Sheargraph, the annuli and the NIAE shear box and imply that the intrinsic strength of the soil is not being measured.

#### 4.1.6.2. Bulk density and moisture content

Two important soil properties are the soil moisture content and bulk density. Field control tests can be destructive or non destructive.

Typical destructive tests are the following:

- the sand cone
- the balloon
- the oil or water method

In all the above tests, soil is removed and weighed. On the other hand the volume of the removed soil is measured by filling the void with sand or liquid. From soil weight and volume the bulk density can be calculated.

Another test for bulk density measurement is the gravimetric test. The gravimetric determination of bulk density consists of weighing small samples of known volume. The Cornelison sampler is an apparatus which facilitates extraction of such samples with minimal disturbance. The soil moisture content can be measured by drying the sampled soil and weighing after drying. The difference in soil weight before and after drying divided by the dry weight of the soil determines the moisture content.

A non-destructive test for measuring the soil bulk density and moisture content is carried out using the nuclear density/moisture gage. The operation of the gage in principle is the measurement of the attenuation of gamma rays or radioactive isotopes, caused by the soil particles. The radioactivity attenuation or scatter is proportional to the bulk density of the material. Three broadly used techniques are the direct transmission, the backscatter and the air gap. Gage calibration against compacted materials of known density is necessary.

#### 4.1.6.3. Soil stress status

In many cases the stress status of the soil *In situ* must be known. The soil stress transducers are of two types:

- moving type, electromechanical

- deforming diaphragm type.

The deforming diaphragm type of soil stress transducer is the most common and is available in three configurations:

- acoustic or vibrating wire
- piezoelectric
- electrical resistance strain gage.

Two important factors affecting stress measurements are the transducer stress-strain modulus to soil stress-strain modulus ratio, which must have a value of ten or greater, and the transducer aspect ratio. Moreover, dense soil pockets or loose soil pockets give over-registration and under-registration of the soil stress status, respectively.

#### 4.1.6.4. Cone penetrometer and Cone Index

The soil Cone penetrometer (CP) and the measuring, recording and reporting procedures for soil strength are described by the ASAE Standard 313.1. The soil Cone penetrometer is recommended as a measuring device to provide a standard uniform method of characterizing the penetration resistance of soils. The force required to press the 30° circular cone through the soil, expressed in pounds per square inch or kilograms per square centimetre, is an index of soil strength called Cone Index (CI).

The penetrometers fall into two general classes, according to the type of load applied:

- the constant rate of penetration test

- the impact-loading test

For the constant rate type the force on the penetrometer that is required to maintain a steady rate of penetration is considered to be a measure of the soil consistency. Measurements are taken continuously with depth. In the impact-loading test, the energy stored in a spring or in a weight at a known higher elevation is used to drive the penetrometer into the soil (Freitag, 1968).

As with many other advancements in modern science and engineering, the cone penetrometer test was developed by the military (U.S. Army Engineer WES, 1944), as an extension of the soil penetrometer work of Proctor (1933) and McKibben (1938). Essentially, it is a high penetration rate bearing capacity test, during which the force on the cone as a function of depth of penetration is recorded. Soil stress per unit area can be calculated knowing the cone base. Since the soil CI is used for calculation of soil stress, use of $kN/m^2$ or kPa would be more appropriate as a reporting unit when the SI system is used.

The cone penetration test is used to predict tractive capabilities of off-road vehicles (Wismer and Luth, 1974), predict draft force of an implement (Gill and Vanden Berg, 1967), assess compaction caused by vehicle traffic and characterize the soil in terms of crop growing ability (Raghavan and McKyes, 1977a). Wismer and Luth (1974) developed an equation describing the dimensionless ratio $C_n$ (Wheel Numeric) as a function of the CI, the tire dimensions width (b) and diameter (d), and the tire load (W). The equation is the following:

$C_n = (CI*b*d)/W$ ....................................4.9

Knight and Freitag (1962) presented a study with regard to the measurement of soil trafficability characteristics using the cone penetrometer. The results were compared with those obtained from shear vane, truss and taper penetrometer tests. No significant difference was measured. The experiments were conducted in the U.S. Army Engineer Waterways Experiment Station. Empirical measurements on bearing-traction capacity were related to CI, measured by the CP. The soil *remolding index* was defined as the ratio of the CI of a compacted confined sample over the CI of the same sample before compaction. The *rating cone index*, the final measure of soil trafficability, was defined as the product of the *in situ* CI and the remolding index. The *vehicle cone index* was defined as the minimum rating cone index necessary for completion of fifty passes of the vehicle over the same path. Vehicle performance versus CI values were presented for fine-grained soils, sand soils and snow. Equations for Mobility Number estimation were presented.

Freitag (1968) presented a study with regard to penetration test for soil measurements, aiming to demonstrate the extent and the limitations of penetrometers. The study was concentrated on the constant rate type penetrometer. Attempts to correlate the penetration resistance with the soil stress-strain properties were not particularly successful.

The cone penetrometer test does not differentiate between cohesion and angle of internal friction in estimating soil shear strength. The same cone index value can be attained with many different combinations of soil cohesion and friction. The penetrometer can be useful when separation of these two soil strength parameters is not required, or when one of these tends to be zero. The cone penetration test can provide the means for evaluation of soil re-orientation and change of the mechanical properties, due to "overcompaction".

According to Freitag (1968) the factors that affect cone penetrometer measurements are; the size of penetrometer shaft relative to cone size, the surface finish of the cone, the size and the shape of the cone, and the rate of penetration. The size of the penetrometer shaft, relative to the diameter of the cone, can influence the results of the test in two ways. The soil displaced by the passage of the cone tends to move outward and upward and to press into the opening of the soil left by the cone. If the shaft is relatively small the pressure relief will tend to reduce the penetration resistance. On the other hand, if the shaft has nearly the same diameter as the cone, the drag of the soil on the shaft could cause an apparent increase in penetration resistance. Placing the force-measuring device at the base of the cone theoretically would solve the problem. In fine-grained soils the roughness of the cone penetrometer surface was not found to have a great effect on penetration resistance. In sand the differences were found significant. No explanation was given. The cone size (base area) and shape (pointed apex angle) are two relevant geometrical cone penetrometer parameters, affecting the penetration resistance per unit area of the apparatus. Figure 4.5 shows the effect of cone size on penetration resistance. The rate of penetration can also affect the pressure required to cause the penetration. Figure 4.6 shows the strength ratio (expressed in terms of the ratio of penetration resistance of the standard 3.226 $cm^2$ cone penetrometer at a penetration rate of 1.83 m/min to the penetration resistance of the same cone at a different penetration rate) versus penetration rate. The penetration resistance is low at low rates of penetration, increasing drastically as the rate of penetration increases. At the upper end of the curve, the trend appears to level off again. In conclusion the opposite trends in the relation between penetration resistance and cone size on one hand, and penetration resistance and penetration rate on the other hand, establish a common basis for cone penetrometer measurements (Freitag, 1968).

Mulqueen et al (1976), presented an evaluation report concerning the measurements of soil strength using the cone penetrometer and a sphere. The underlying concept was the measurement of soil shear, compressive and compound strength

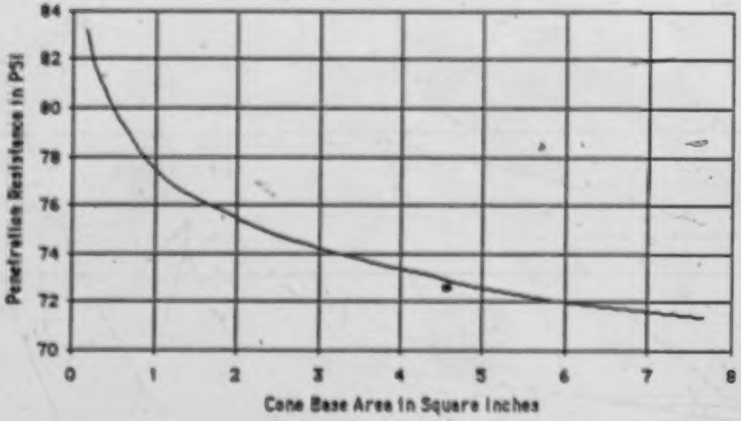


Figure 4.5. Cone size versus penetration resistance (Freitag, 1968)

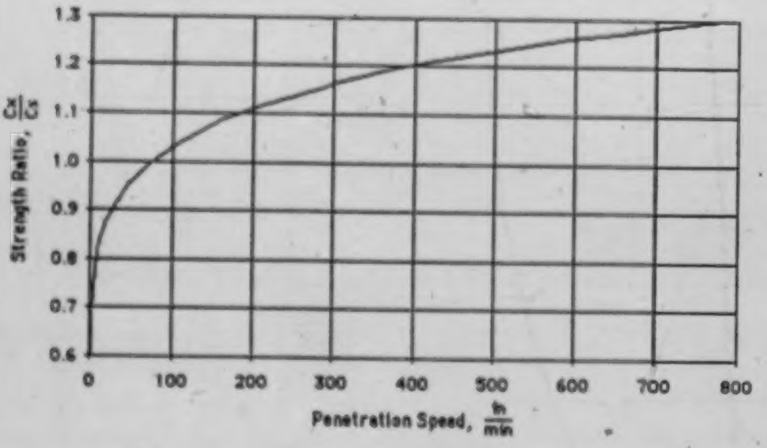


Figure 4.6. Strength ratio versus penetration speed (Freitag, 1968)

and soil-metal friction using a sharp and a blunt probe. The researchers concluded that the relative proportions of the soil strength components vary with soil moisture content, with cone index becoming increasingly insensitive to shear strength or compressive strength changes as moisture content increases. The penetrometer was found useful for comparing the relative strengths of soils under conditions of similar moisture content and structural state.

Wells and Lewis (1980) describe a method for remote electronic acquisition of soil CI. The scope of their work was the development of a manually transported, one-person operated penetrometer, electronically measuring and recording a large number of force-penetration relationships, individually identifiable. Information storage and transmission to a mainframe for further processing were considered. The electronic capabilities of the penetrometer were based on a microcomputer. No description of the hardware components were presented.

Upadhyaya et al (1982) presented a study of the performance of controlled field tests to relate CI to bulk density and moisture content. The modeling of the prediction equation for CI employed the dimensional analysis technique. The experiments were conducted in two different locations. A nonlinear regression model was employed for statistical analysis. Experiments with varying bulk densities at a constant moisture content and varying moisture content at a constant bulk density were conducted. The relationship between CI, bulk density $\rho$ and moisture content $\theta$ was found to be,

$$\alpha(CI/K)=a(\rho/\rho_s)^n e^{-b\theta} \quad \text{.......................} 4.10$$

where a, b and n are positive constants, $\rho_s$ is the soil particle density, K is the bulk modulus and $\alpha$ is a non-dimensional scaling factor. An important inference made from this study concerned the contribution of the rotary tiller in soil uniformity, at least in terms of moisture content.

Ayers and Bowen (1983) determined soil density profiles employing an existing soil failure theory (bearing capacity analysis for deep foundations). The purpose of the study was to investigate whether a one to one relationship exists between penetration resistance and soil density for all soil moisture contents. The validity of the model was examined with several sand-based soils in the laboratory, using the Torsional (Ring) Shear test, and in-field conditions, using the CP for penetration resistance measurements. Using a multiple linear regression analysis the soil strength parameters were expressed in terms of bulk density and moisture content.

Tollner and Clark (1984) compared the performance of a lubricated and a conventional soil CP. A continuous flowing polymer was employed as a lubricant. Various soils and treatments were examined. The purpose was the investigation of a CP that would produce data with reduced variation about sample means or increased differences in respective treatment means. CI means and variances were measured and compared for the CP. The researchers found a higher coefficient of variation with the lubricated CP.

Experience indicates that the cone penetrometer is less successful in measuring shear strength than bearing capacity since the cone penetration resistance is more sensitive to soil disturbance than the bulk density, due to deformations caused by the traction members.

### 4.1.7. Soil bin facilities

Wismer (1984) presented a survey concerning soil bin facilities characteristics and utilization. In this survey the dimensions, the capabilities and the utilization of the soil bins are presented along with basic statistics.

Most of the reported facilities are of an indoor type. In terms of functional test capabilities of the soil bin facilities, tillage is the most common with wheel traction immediately following.

The operating soil bin facilities use a wide variety of soils, with loams being predominant. Also, variations in moisture, density, cohesion, angle of internal friction and cone index value have been reported. Artificial soils are used, with an oil-sand-clay mixture being the dominant combination.

The soil strength and condition tests in use, for correlating machine performance and for controlling the preparation of test sections, are the cone penetrometer, the ring/plate shear, the gravimetric moisture and density, the Atteberg limits (liquid and plastic), the triaxial shear, the plate penetration, the unconfined compression, the nuclear moisture-density, the tensile strength and the vane shear. The aforementioned soil tests were presented by rank order of use.

Not all the laboratories support tillage test facilities. Among the soil bins that support such a facility 81% can test passive tools, 46% can test powered tools and 35% can test both passive and powered tools.

Not all the laboratories supported traction test facilities. Among the soil bins that support such a facility 91% conduct wheel traction tests, 27% conduct track traction tests and 23% conduct both types of tests.

Utilization of the soil bin in research encompasses educational institutions and manufacturers. The range of subjects addressed by the laboratories includes traction efficiency, tillage tool shape and force relations, tool performance and soil-machine modeling. Some unusual research subjects reported are, rimless wheel, boat-type tillage machine, soil reinforcement and soil anchors. Soil models for soil-machine systems were also the subject of research effort, including critical state soil mechanics principles, cycloidic properties of soils, two-dimensional and three-dimensional finite element models.

## 4.2. Traction devices and their properties

The traction devices or traction members constitute the interface factor between tractor and soil. The traction devices are divided into the following two major classes:

- track-type traction devices
- rubber tires.

The terminology that applies to traction devices has been presented in the chapter titled Terminology. Only rubber tire properties and behavior will be analyzed. Also, very brief information with regard to rim sizes and tire-rim matching will be presented for integrity purposes.

Hereafter, the terms traction devices and traction members will apply interchangeably to rubber tires. Moreover, the term motion resistance will be regarded identical to rolling resistance and either term can be used interchangeably.

### 4.2.1. Tire classification

Rubber tires are classified according to:

a. construction

b. use.

According to their construction rubber tires are divided into Bias-ply or diagonal tires and Radial tires.

The Bias-ply or diagonal tire has the cords in the individual plies of the carcass arranged in a diagonal from bead to bead configuration. Structural stiffness is obtained by alternating the cord direction of each ply producing a criss-cross cord matrix.

The Radial tire is a two-element structure. From the inside to the outside of the tire there is a group of plies with the cords arranged in a radial configuration from bead to bead, superimposed by a rigid multiple-ply belt with the cords arranged in a near circumferential configuration.

Bohnert and Kenady (1975) presented a comparative analysis of Radial and Bias-ply drive wheel tractor tires, including brief information about tire construction. Figures 4.7 and 4.8 show the aforementioned tire construction differences.

The advantages of the radial over the bias-ply tires will be examined in a subsequent section.

A different way to classify tractor tires is according to their use. The classification scheme is as follows:

- rear agricultural tires
- rear industrial tires
- front tractor tires
- implement tires
- log-skidder tires

Within each of the aforementioned classes the tire design differs, so that the tire becomes more efficient under certain soil conditions.

In agricultural practice the powered traction members can be in a single, dual or triple configuration, in order

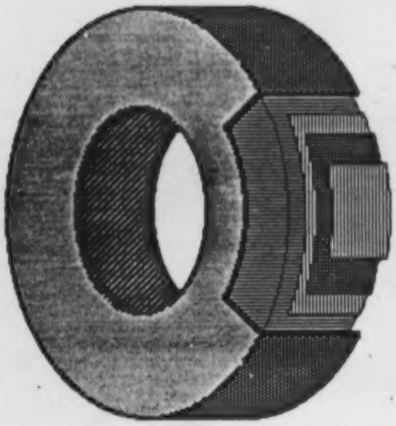


Figure 4.7. Radial ply tire construction

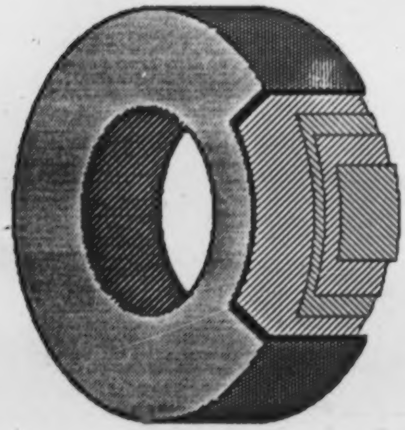


Figure 4.8. Bias ply tire construction

to provide better traction and flotation, and to cause less soil compaction. The unpowered traction members are used in a single configuration in order to avoid excessive rolling resistance.

### 4.2.2. Rim and rim-tire matching

The rim is the metal construction that is attached to a tractor axle and on which the rubber tire is mounted. The two rim dimensions that are important for rim-tire matching are, the rim diameter (ASAE Standards, 1984) and the design rim width (TRA Yearbook, 1984). ASAE S219.2 (SAE J712a) refers to rim specifications such as rim size, inset (reversible rim) and outset (nonreversible rim), and maximum rated radial wheel load. The agricultural tires are designed to carry a specified load at a specified inflation pressure when mounted on a specified width rim (GOODYEAR, 1984).

The rim-tire matching is a very important factor for proper performance and long life of the tire. According to the Farm Tire Handbook (GOODYEAR, 1984), use of a rim wider than recommended results in a flattening of the tread face. Under loose soil conditions traction may be improved; however, in hard soils the tractive effort is reduced. On the other hand use of a narrower rim than the recommended, results in both reduced traction and increased wear. In both cases the chances of tire damage are increased considerably and extra caution is advised by the tire manufacturers with regard to rim-tire matching.

Hoemsen (1984), using computerized finite element modeling and analysis, attempted to determine the rim change in order to withstand higher static loads. Various materials were investigated. Three load cases were analyzed. Rim structural performance for various materials and sizes was determined in terms of the performance factor. The performance factor is determined by the ratio of the endurance strength of the material to the maximum combined stress level in the component, and should never be less than one. Using a stronger material for the rim was proven more advantageous, in terms of percent endurance limit increase, than increasing the thickness of the standard material.

### 4.2.3. Tire parameters

Each tire is designed with specific characteristics in order to be able to comply with different tractor designs and soil conditions. The tire parameters that affect tire performance are the tire size, the ply rating, the inflation pressure, the load factor, the lug dimensions, the tire effective arm and deflection, the tire diameter, the tire width and the aspect ratio.

Domier (1978) presented a comparison of the tire parameters on a Dynamic Traction Ratio versus Slip basis, determined from the results reported by the University of

Nebraska tractor test reports. The way these parameters affect tire performance is also referenced.

Tire construction is a factor that affects tire performance, however, this aspect will be examined separately. The aforementioned parameters are analyzed in the following sections.

#### 4.2.3.1. Tire size

The tire size is probably the most important tire parameter examined when a tire is to be mounted on a tractor. Tire manufacturers encode the tires uniformly according to a code approved by the Rubber Manufacturers Association. The code was created in the interest of simplifying reference to specific types of agricultural tires, regardless of the manufacturer (GOODYEAR, 1984).

A comparison of the tire dimensions of tires made by different manufacturers, (GOODYEAR, BFGoodrich, Firestone) reveals differences in the tire dimensions as low as a few tenths of an inch (2-5 mm).

Dwyer et al (1974a,b) working in the NIAE, UK, developed a Handbook of Agricultural Tyre Performance, including performance characteristics of selected tire sizes and the associated terminology. Figure 4.9 shows a section of the traction member with the associated dimensions, as they were presented in the aforementioned Handbook. The terminology is compatible with the one included in the ASAE

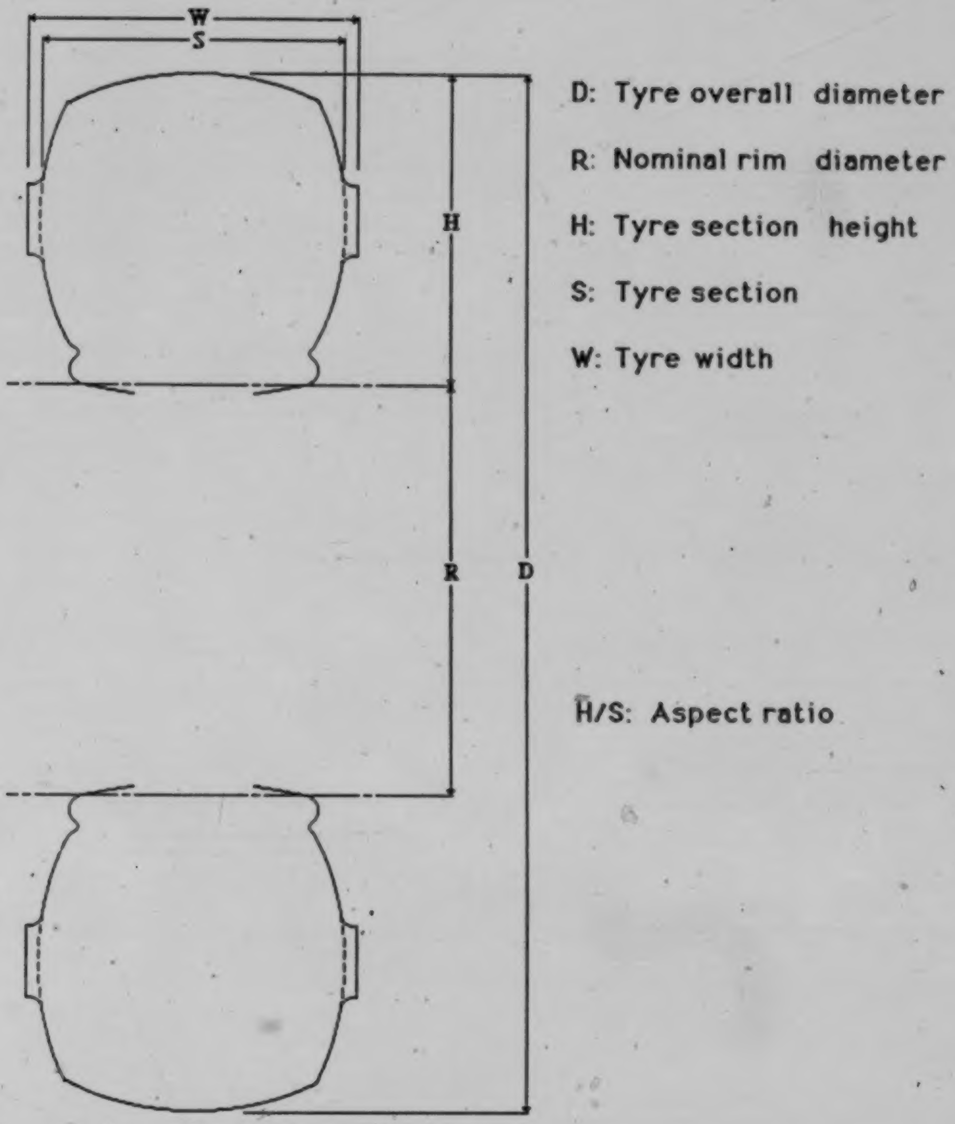

W
S
H
R
D
D: Tyre overall diameter
R: Nominal rim diameter
H: Tyre section height
S: Tyre section
W: Tyre width
H/S: Aspect ratio

Figure 4.9. Definitions of tire dimensions

(Dwyer et al, 1974)

Standard S296.2 (1984).

The methodology of marking and reporting tire sizes encompasses three main methods (Dwyer et al, 1974b). The first method or form, which is the simplest, is used for tractor steering wheel tires, trailer and implement tires. The first number represents tire section and the second number represents the nominal rim diameter. The format of reporting these tires is *tire section-rim diameter*. The second form, which is the dual marking system, is used for tractor driving wheel tires which were originally marked as for steering wheel tires. However, when wide rims were introduced and the measured tire section changed, the need for a dual marking system became apparent. The dual marking system was intended to be for an interim period only, with the new marking eventually becoming standard. Newer sizes do not have the older markings. The format of reporting these tire sizes is *new tire section/old tire section-rim diameter*. The last form is used for high flotation or low section height or low aspect ratio tires. The format of these tires is *tire section/aspect ratio (%)-rim diameter*. However, low section height tires are reported by the manufacturers by appending the letter L to the tire section, giving no further information with regard to tire aspect ratio. The tire size affects indirectly the tire performance through the tire dimensions.

#### 4.2.3.2. Ply rating

The ply rating of a tire is a measure of its resistance to bursting under pressure, identifying the maximum safe inflation pressure and the maximum allowable load on a tire used in a specific type service. Originally, the ply-rating was the number of cord plies used in the construction of the tire. The use of stronger materials in tire construction made this number an equivalent strength index (ASAE, 1984).

Domier (1978) found no effect of ply-rating on tire performance on concrete. The ply-rating is another tire index indirectly affecting tire performance through the maximum allowable inflation pressure and load on the tire.

#### 4.2.3.3. Inflation pressure

The tire inflation pressure is a factor that directly affects tire performance and usually is combined with the tire load.

Domier (1978) reported that for tires operating on a concrete surface a 14 kPa (2 psi) increase in tire pressure, coupled with a corresponding increase in tire load, resulted in a 0.5% increase in slippage, whereas a 28 kPa (4 psi) increase in pressure caused a 1% increase in slippage. When duals with reduced inflation pressure were used a decrease of 1.5 to 3.0% in tire slippage was recorded, as compared to single tires with high inflation pressure.

Tire inflation pressure directly affects tire performance, through the tire shape and the tire-soil contact area, and indirectly through the allowable dynamic load on the traction devices, therefore the ballasting recommendations. Tire underinflation has the same effect as tire overloading, which is tire overdeflection causing uneven and rapid tire wear. Tire underinflation causes an increase in soil-tire contact area, providing better traction, particularly under poor soil conditions, in exchange for higher tire damage risk. On the other hand, tire overinflation reduces traction due to reduced soil-tire contact area and reduced tire flexing characteristics. When the tire is overinflated the tread wear concentrates at the tire centerline area. (GOODYEAR, 1984).

When the tire is ballasted with liquid ballast (solution of calcium chloride in water), the tire pressure remains the same. Only 75% of the tire volume should be filled with liquid ballast. When checking the true operating pressure of liquid filled tires the valve should be at the bottom of the tire and the tire temperature must be low (GOODYEAR, 1984). In liquid ballasted tires, the 25% of the tire volume occupied by air maintains the flexing characteristics of the tire which then can absorb 25% more impact than a tire which is liquid weighted to 100%.

When a driving tire is operating in a furrow (mouldboard plowing operation) or in the down slope position (hillside farming operation) an increase in the tire inflation pressure of 28 kPa (4 psi) is recommended in order to avoid sidewall buckling. When a driving wheel operates in a high torque service, maximum inflation pressure for the tire size and ply-rating is recommended (GOODYEAR, 1984).

Dwyer (1975), working at NIAE, reported that the performance of a tire operating in a furrow, compared to a tire of the same load and pressure operating on the soil surface, was not substantially different in terms of tractive efficiency. The higher coefficient of traction for the tire in the furrow was compensated by the higher coefficient of rolling resistance for the same tire.

Burt and Bailey (1981) presented a study, conducted in the soil bin of the NTML using a radial tire, investigating the effects of load and inflation pressure on tire performance. Burt et al (1983) continued the study of the effects of ballast and inflation pressure on the tractive efficiency of selected bias and radial-ply tractor tires operated under field conditions. The experiments consisted of the measurement of various load and inflation pressure combinations under constant drawbar pull. Generally, the results did not show a consistency, implying that tractive efficiency cannot be maximized at a particular level of drawbar pull by selecting dynamic load and inflation pressure values which yield minimum values of travel reduction. The tractive efficiency was found to be maximum over a wide range of dynamic load and inflation pressure values, and the need for an automatic control system for the two parameters was evident.

Hemingway et al (1982) presented a prototype system to control tire inflation pressure on-the-move. Optimum tire performance was obtained by matching tire inflation pressure and tire deflection with varying levels of tire loading and ground conditions. The goal was an increase in traction with a parallel reduction in soil compaction. The analysis for the inflation pressure control was based on the influence of the tire inflation pressure on traction, on soil compaction and on safety aspects. Differences of tire deflections on concrete and in-soil were measured for the same load and pressure. Tires were found to deflect less in-soil. The prototype consisted of a single cylinder air compressor with a capacity of 2 L/s and the associated pipework. The air was delivered to the centerline of the axle and from there to the tire valve through a rotary valve. Each tire inflation pressure was tested independently. The tire pressure rate of change varied from 0.15 to 0.20 bar/min. Increased deflection resulted in reduced wheel slip at constant level of drawbar pull or increased drawbar pull at constant level of wheel slip. A point shown from the tests was that deflection was proportional to tire self cleaning and traction ability. The system would require a method of measuring in-soil tire deflection. A gage installed in the tire would be the most appropriate. Configurations for such a system are presented in the section associated with tire deflection.

### 4.2.3.4. Load factor

The load factor has been arbitrarily defined as the ratio of the static load on the driving wheels to the allowable load, as specified by the TRA Yearbook (1984). Increase of the load factor on concrete results in an increase in travel reduction and a decrease in tractive efficiency (Domier, 1978).

The load factor effect is present when inflation pressure versus tractive performance measurements are taken. The load factor is meaningful for a specified inflation pressure.

### 4.2.3.5. Lug parameters

The two lug parameters that are important in determining tire performance are the lug angle and the lug height, both included in the ASAE Standard S296.2. The two angles that are used by the tire manufacturers are 45° and 67°. Surprisingly, the tire manufacturers report the 67° lug angle tires as 23°, measuring the lug angle from a line perpendicular to the one proposed by ASAE. Many of the contemporary tires do not have a unique lug angle across the lug. In such a case an on-average lug angle can be estimated. One manufacturer reports a radial tire with such a lug design having an on-average 40° lug angle (50° according to S269.2). The 67° lug angle tire does give better traction on most soil under dry conditions. On the other hand the 45° lug angle tire performs better under wet soil conditions. Tires with improved tractive abilities use narrower lug angles for improved performance under adverse soil conditions. In comparing tires with 67° lug angle versus tires with 45° lug angle operating on a concrete surface, Domier (1978) did not obtain consistent results. However, an increase in tractive efficiency was detected with 45° lugs.

The other important lug parameter is the lug height. The role of the lug height is completely different when a tractor is tested on concrete and when operating in-soil. When the tractor is tested on concrete the smaller the lug height, the better the tractive performance. Nebraska test code does not allow a lug height less than 65% compared to a new tire. Usually, tractors tested in Nebraska are equipped with tires close to this wear limit.

When the tires operate in-soil the lug height requirements differ with soil conditions. In dry, hard soil large lugs perform worse, since they have difficulty to penetrate the soil surface. In wet, soft soil the greater tread depth improves tractive performance, providing extra thrust exceeding the additional motion resistance. Greater lug height facilitates greater lug surface, thus decreasing soil shear stresses.

Dwyer (1975) comparing five tires with 0, 20, 35, 50 and 75 mm lug height, found that the tires with 20, 35 and

50 mm lug height performed similarly operating on an average soil, the 75 mm lug height tire performed better in wet soil conditions and the tire with no lugs performed better in a few dry, loose soils. Motion resistance showed a strong tendency to increase with lug height increase.

#### 4.2.3.6. Tire effective arm and deflection

The term tire effective arm is used synonymously to tire rolling radius and is calculated as the difference of the tire radius (overall tire diameter divided by two) and the tire deflection. The tire effective arm is used extensively in the computer program that will be presented in a subsequent chapter and is used instead of the term rolling radius. The purpose of this innovation was to avoid confusion with the tire radius or the tire loaded radius. The tire effective arm takes into consideration the tire deflection, as calculated by a generalized load-deflection relationship. Tire load is considered the dynamic load on the axle, accounting for weight transfer from the front to the rear of the tractor.

Recent information provided by Kenady (BFGoodrich), Charles (Firestone) and Ellis (GOODYEAR), with regard to load-deflection relationship, enabled the derivation of an equation, based on certain assumptions. The equation and the associated analysis are presented in chapter six. The calculated effective arm is used in the equations for estimating moments around the rear axle.

Measurement of the tire deflection is always desirable, though not easy to obtain during in-soil operations. It is generally accepted that the rubber tire, for the same load and inflation pressure, deflects less in soil than on concrete, possibly due to soil deformation (yielding). Knight and Green (1962), working at the U.S. Army Waterways Experiment Station, installed five potentiometer assemblies inside a tubeless tire. The potentiometer assembly consisted of a linear and a circular potentiometer. All five potentiometers were mounted on the rim and transmitted their data to an eighteen-channel direct-writing-oscillograph through a twenty-channel slip ring mounted on the axle hub. Briefly the tire deflections were found to be dependent on tire load and inflation pressure, type of surface upon which the tire operates and tire velocity. The magnitude of influence of each of these factors was approximately in the order in which they are listed. A similar design to the one presented by Knight and Green reportedly has been developed by Freitag and Smith (1966).

Burt et al (1984b), working at NTML, presented a three-dimensional, sonic digitizing system for tire deflection measurements. The system was developed to permit the estimation of the direction of the stress vectors at the soil-tire interface and the tire strains in the radial, tangential and lateral directions, with respect to the wheel rim. Lug deformation studies were also conducted. The innovation of the system was that no physical contact was required between the sensing device and the device being studied. The system consisted of sound emitters and receivers and the associated electronics for signal measurement and interpretation. The response of the system was quite satisfactory and repeatable.

#### 4.2.3.7. Tire diameter

The tire diameter is specified in ASAE S296.2 and is reported by the tire manufacturers as overall tire diameter.

Domier (1978) reported a decrease in travel reduction and an increase in maximum tractive efficiency with an increase in tire diameter for tires operating on a concrete surface.

Tires with large diameter are necessitated by the need for better flotation, less soil compaction and less motion resistance. On the other hand, larger tires require more input torque in order to develop the same thrust as exerted by smaller tires. Increasing tractor size, with subsequent increase in tractor weight and engine power, conforms with the use of larger tires, since more bearing capacity is required (load factor) and more torque is delivered to the traction members.

#### 4.2.3.8. Tire width

The tire width is specified in the ASAE S296.2 for a new tire. Tire manufacturers report the section width, not including protective ribs and decorations.

Domier (1978) reported that no differences in dynamic traction ratio and tractive efficiency were obtained on concrete surface over the normal traction range for two tires differing in width by 33%.

### 4.2.4. Tire ballasting

The traction or pulling power that a tire can exert is proportional to the weight carried by the tire. In turn the weight carried by the tire is determined by the tractor design. Any further increase of the tractor weight is achieved using ballast. The ballast is usually added on the powered wheels. If the steering stability of the tractor is inadequate additional weight may be added on the front end of the tractor.

The most common ballast in use is either cast iron mounted on the rim or liquid ballast inserted in the tire. The composition of the liquid ballast, according to the recommendations of the tire manufacturers, can vary from pure water to a solution of 60% $CaCl_2$, depending on the prevailing temperatures. The wide acceptance of liquid ballast was mainly due to its low cost and its satisfactory performance. The major drawback for ballasting the tire with $CaCl_2$ is the need for special equipment, preventing in-field readjustment, as it is the case for cast iron ballast.

Tire load and inflation pressure jointly affect the tangential pull (thrust) the tire can exert. Maximum tangential pull is attained by the tire when carrying 80 to 95% of the rated load at specific inflation pressure. For each unit of weight added the tangential pull is increased by a fraction. Both weight and pull are expressed either in kN or pounds (lbs). GOODYEAR (1984) has given examples of ballast efficiency as percentage of tangential pull increase per unit of ballast added, under various surface conditions:

| | |
|---|---|
| Concrete | 66% |
| Dry Clay | 55% |
| Sandy Loam | 50% |
| Dry Sand | 36% |
| Green Alflfa | 36% |

Domier and Willans (1978) investigating maximum versus optimum tractive efficiency reported that a 60 kg/kW weight to power ratio on a two-wheel drive tractor was adequate to attain maximum tractive efficiency at field velocities over 8 km/h. A loss in efficiency of 3 to 5% was observed at lower velocities. Capital costs and field capacity versus added ballast were also estimated.

Harrison (1970) presented a study on the way the tractor ballast affected the maximum tractive efficiency. Starting from the form of the quadratic curve that represents tractor drawbar power loss versus added ballast, an attempt was made to estimate the ballast at which the minimum of the function occurs. The ballast was estimated as a linear function of the drawbar pull. The function was defined by setting the first derivative of the total power loss to the load equal to zero.

Bashford (1975) presented a study concerning the effects of ballast on the tire slippage and the use of the maximum available drawbar power. He concluded that the optimum operation slippage should range from 10% for firm soil to 15% for soft soil. He also made available coefficients to use to multiply the PTO horsepower to obtain tractor weight in pounds, for typical Nebraska firm, tilled and soft soils.

A very important aspect in ballasting a tractor is the weight distribution for a two-wheel, a four-wheel and a front wheel assist tractor. A common mistake in ballasting a tractor is the inappropriate weight distribution between front and rear of the tractor, taking into consideration the dynamic weight transfer. The tractor weight distribution for the three tractor types, in terms of front to rear static weight ratio, are represented by the following orders of magnitude:

a. 2WD, 30:70

b. FWA, 40:60

c. 4WD, 60:40

The reason for ballasting the 2WD tractor so lightly on the front end is that the ballast should be adequate to maintain steering stability providing at the same time the minimum motion resistance possible. Since traction is obtained through the rear wheels, most of tractor's weight should be concentrated on the rear of the tractor.

The reason for ballasting the FWA tractor in a 40:60 ratio is that part of the traction is provided by the front wheels, therefore a weight comparable to the size of the front tractive devices should be maintained on the front of the tractor.

The reason for ballasting the 4WD tractor more heavily at the front is that weight distribution equilibrium is obtained under load, considering the weight transfer from front to rear. The weight is distributed over equal size traction members.

Bloome et al (1982) carried out an experiment at Oklahoma State University, in order to demonstrate the effect of ballast in tractor-implement matching. An Allis-Chalmers 2WD tractor was tested in-field at three ballast levels using a towed implement. The tractor weight distribution was 25:75. The results were compared with theoretical results obtained from prediction equations given in the ASAE Standards. For the four soil Cone Index values that were assumed, the travel speed at maximum Tractive Efficiency was independent of soil strength.

Bloome et al (1983) presented a literature compilation, comparing the ASAE D230.3 prediction equations with the single wheel test results reported by NIAE (Dwyer et al, 1976) in terms of pull at 20% slip, motion resistance and wheel numeric. Equations relating tractor weight per unit of PTO power with actual ground speed were also compared. Equations providing an estimate of ballast as a function of ground speed under specific tractive efficiency were presented. Static weight distribution recommendations were reported for 2WD, FWA and 4WD tractors in terms of rear weight as a percentage of total tractor weight. The figures reported were for 2WD tractors, 75% for towed implements, 70% for semi-mounted implements, 65% for integral implements; for FWA tractors 60%; for 4WD tractors, 40% for mounted implements and 35% for towed implements. Comparing 2WD and 4WD tractors they concluded that ballasting recommendations (kg/kW) at the same field speed should not be considerably different, though 4WD tractors can better utilize higher mass-to-power ratios. Optimum tractor mass was found proportional to engine power output. Ballast should not be increased on soft soils. The recommended minimum ballast was found approximately equal to the recommended optimum ballast at 80% engine loading.

Lyne et al (1982) investigated the effects of ballast on the specific fuel consumption. The experiments were carried out on a clay soil and the parameters monitored through the test were input torque to each drive wheel, angular velocity of the driving wheels, drawbar pull, forward velocity, engine speed, fuel consumption and time. All the sixteen combinations of four static loads and four inflation pressures were considered. During all the experiments the engine was run at maximum speed in third gear. In conclusion low values of in-field specific fuel consumption can be attained at high levels of output power by simultaneously optimizing engine performance and Tractive Efficiency. Engine performance optimization was attained by selecting an appropriate gear ratio and engine speed for a given load. Tractive Efficiency optimization was attained by selecting the appropriate dynamic load and inflation pressure.

### 4.2.5. Bias-ply versus radial tires

In comparing bias-ply and radial tires a number of features have to be considered. The difference in cord arrangement gives different performance characteristics. The radial tire cords run from bead to bead at right angles to the direction of rotation, as compared to the diagonal pattern of the traditional bias ply tire cord layers. Radial construction results in increased tire flexibility to conform better with ground contours. Radial tires, under the same load conditions, perform with less slip, therefore they travel faster and develop higher drawbar power, increasing the tractor's Tractive Efficiency.

In the Agricultural Engineering Journal (June 1975), an economical comparison among bias-ply and radial tires was presented. At that time the price of the radials was considerably higher than the equivalent bias-ply tires. However, a global analysis of the radial tire benefits resulted in the conclusion that radials are here to stay. Higher drawbar power, fuel efficiency, field efficiency, less slip and greater life expectancy for radials over bias-ply tires, were reported as the major advantages.

Inversion of the slip-drawbar pull relationship shows that radials exert more drawbar pull at a certain level of slip compared to bias-ply tires. In order to increase drawbar pull for bias-ply tires, additional ballast is required. Beside the fact that tractor weight increase is costly, an axle load increase is not always possible without changing tire ply rating.

The radials lower slippage, the increased traction, the better flotation and the reduced soil compaction are attributed to their longer and wider footprint, as an immediate result of their flexing characteristics.

Alberta Agriculture, Agdex 740-1/1983, presented an analysis of radial tires for agricultural tractors in terms of various performance parameters. Reduced slippage, higher drawbar pull at specific slip level, increased flotation, improved fuel efficiency and longer tire tread life for radial tires, make them advantageous over bias-ply tires, especially for larger tractors. The aforementioned advantages outweigh and justify the higher price of the radial tires.

Bohnert and Kenady (1975), presented a comparative performance analysis of bias-ply and radial drive tires, and delineated the basic radial tire mechanics, which make the performance improvements feasible. Loaded radial tires show greater vertical deflection, resulting in an approximately 22% increase in contact area. This is obtained through the difference of the sidewall and tread moduli of radial tires, allowing a larger portion of tread to contact the ground for a given tire load. The researchers found that radial tires in the 0 to 30% slip range exhibit higher Tractive Efficiency and Pull Ratio, both on a tilled soil and on sod for both molded and commercial tires. Testing of both tire types revealed better response of radials in "carcass buckling" when subjected to high torque levels, as compared to bias tires. The buckling is caused by compressive forces applied to the tire. The difference in behavior is explained by the stress-cord position relative to the ground relationship of the tires. The radial low modulus sidewalls allow the design to behave like a torsional spring.

Radial tires exhibit improved ride abilities since they transmit less excitational force than bias tires when an obstacle is encountered. The bias-ply tire effective arm exhibits greater dependency on load, as compared to radial tires. That makes radial tires more suitable for 4WD tractors, helping maintain comparable velocities of the two axles.

Turnage (1976) described towing resistance as the sum of resistance from soil-tire interactions and from internal motion resistance. The tire performance comparison used four radial tires, two bias-ply tires and two soils. The experiments were run at the Waterways Experiment Station using single tire laboratory tests. Flexible versus stiff tire performance evaluation was carried out using dimensionless wheel numerics. These wheel numerics are used by the OECD tractor performance simulation model as Mobility Numbers. Turnage concluded that flexible tires at deflections up to 35%, exhibit closely related clay-tire and sand-tire numerics for a broad range of tire stiffness and deflections. The numerics are closely related to soil-tire interactions. Variability was observed on the effect of the tire internal motion resistance on the in-soil total towed force coefficient for different tire stiffnesses.

Charles (1983) presented a study concerning the effects of tire load and inflation pressure on radial tire traction performance. Three different tire static loads at constant inflation pressure and five different inflation pressures at constant tire static load were tested. In conclusion he stated that the adjustment of both the tire ballast and the inflation pressure can provide optimal tractive field performance. Peak Tractive Efficiency was observed at 10% slip. The peak Tractive Efficiency at constant inflation varied between 79% and 83% for the sod, and between 71%

and 74% for the tilled soil. The peak Tractive Efficiency at constant load varied between 77% and 82% for the sod, and between 60% and 72% for the tilled soil.

#### 4.2.6. Dual tires

The use of duals on tractors was a natural consequence of the increase of tractor weight and power. The major advantage of duals is that they can sustain the higher tractor weight at lower inflation pressures, improving Tractive Efficiency and causing less soil compaction.

The advantage of duals as compared to singles, is emphasized as soil moisture content increases. Besides the increase in tractive performance when duals are used, tractor flotation is another factor. Duals, and even more so triples, assure better tractor flotation and trafficability on wet soils, affecting the timeliness of the farming operations.

Domier and Friesen (1969) found no significant difference between singles and duals under non-cohesive soil conditions. On wet clay soils (cohesive) the duals increased traction by as much as 18%.

Dwyer and Heigho (1984) studied the tractive performance of large tractor drive wheel tires in comparison with duals. In conclusion they found that the tractive performance of the wider tires was inferior to that of the conventional sizes, due to the fact that the drawbar pull increases less in proportion to the load increase and the motion resistance increases more in proportion to the load increase. The use of duals maintains the proportions and provides additional increase in tractive performance if the tires are spaced by one tire width. The authors stated that the existing relationships can adequately predict the performance of dual wheels of conventional sizes.

### 4.3. Tractor design

In this section the major tractor parameters will be examined, being classified into primary and residual parameters. Though many of the parameters are affected both by the soil and the tractive device, an effort will be made to stay as close as possible to the mechanics of the system.

The pertinent terminology with regard to tractor parameters is given by the ASAE Standard S296.2.

#### 4.3.1. Primary tractor parameters

Primary parameters are defined the ones that are functions of tractor design exclusively. These parameters are the engine speed, the gear, the PTO power, the axle power, the axle torque and finally the front, rear and total static weight.

The starting point in analyzing tractor behavior is the engine power-engine speed or the engine torque-engine speed relationships. These relationships characterize tractor engine behavior and the relevant information is given by the PTO test and the tractor "lugging ability". A desirable torque curve is one that increases significantly as speed decreases and is therefore stable. Such a torque curve results in a minimum of engine speed variation. Engine speed is an index of the engine torque and power, and hereafter will be considered as such (Liljedahl et al, 1979).

The operating gear is associated with the torque and power transmission ratio to the differential and the final drive. The torque, power and angular velocity of a powered axle are tractor design parameters in the sense that they are exclusive functions of the engine speed and the operating gear. Also they are independent of wheel and soil parameters.

Transmission ratio information for each gear, through the tractor power train is not provided by the Nebraska Tractor Test Report. The transmission ratio for a specific gear can be calculated as the ratio of the engine speed over the axle speed. This method is used by the OECD simulation model to compensate for missing information, when the Nebraska Tractor Test Report is used as a source.

The power and angular speed measured on the PTO is an index of engine performance knowing the engine to PTO transmission ratio from the PTO performance test.

The front, rear and total static weight are tractor parameters and are fairly constant. Static tractor weight and weight distribution can be modified using additional ballast. The static tractor weight distribution is the basis for dynamic weight distribution calculation, due to weight transfer from the front to the rear of the tractor.

The tractor parameters described so far are the basis for in-soil tractor performance prediction and they characterize the tractor as a "black box".

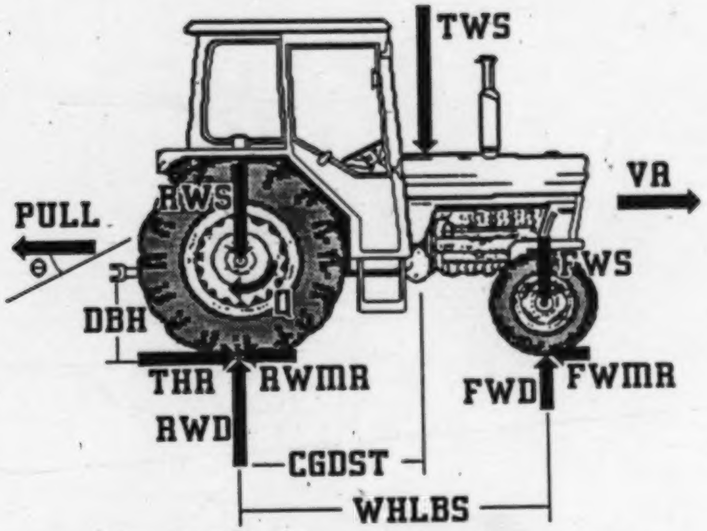
A tractor parameter that was not considered throughout this study is the fuel consumption. Khalilian et al (1984) presented various revised fuel consumption equations for diesel engines. Fuel efficiencies of naturally aspirated, turbocharged and turbocharged-intercooled tractors were compared using regression analysis. The field data were in agreement with the estimated values, using the modified equations. A comparison of the modified and the fuel economy equations included in ASAE D230.3 against measured values, showed that the ASAE equations overpredict fuel consumption or underpredict fuel efficiency by more than 20%. Turbocharger and turbocharger-intercooled engines showed increased fuel efficiency.

Pang et al (1984) presented a method of indicating tractor fuel consumption by measuring the temperature of the exhaust gas. The researchers observed a nearly linear relationship between fuel consumption and exhaust temperature at a certain distance from the engine, expressed in the form of a third degree polynomial. The standard error of estimate of the method was found to be 0.07 L/ha.

Jurek and Newendrop (1983) presented in-field fuel efficiency comparisons of various John Deere tractors, using John Deere's programmable drawbar dynamometer (Dyna-Cart). The parameters tested were dual versus single rear tires, radial ply versus bias ply rear tires, FWA (Mechanical Front Wheel Drive) versus 2WD, and the effect of shifting on-the-go to match the engine speed to the load. With respect to fuel efficiency, the researchers found that in varying load conditions shifting on-the-go provided an increase of up to 10% in efficiency (ha/L). Radial tires caused an increase of up to 10% in fuel efficiency, particularly for the 2WD tractor. The FWA tractors showed an improvement of up to 19% in fuel efficiency under poor tractive conditions.

### 4.3.2. Residual tractor parameters

The residual or tractor performance parameters describe tractor performance and they are affected by the properties of both the soil and the tractive devices. The residual parameters are the tractor thrust, the drawbar pull, the drawbar power, the weight transfer and the dynamic front and rear weights, the motion resistance, the slip, the travel ratio, the theoretical and ground velocity, the Dynamic Traction Ratio (DTR), the Gross Traction Ratio (GTR), the Force Efficiency, the power coefficient and the Tractive Efficiency (TE). Figure 4.10 shows the important geometrical


TWS
VA
PULL
θ
RWS
FWS
Q
DBH
THR
RWMR
FWD
FWMR
RWD
CGDST
WHLBS

TWS : Tractor Static Weight
RWS : Rear Static Weight
FWS : Front Static Weight
RWD : Rear Dynamic Weight
FWD : Front Dynamic Weight
PULL : Drawbar Pull
DBH : Drawbar Height
THR : Thrust
FWMR : Front wheel motion resistance
RWMR : Rear wheel motion resistance
CGDST : distance of center of gravity from rear axle
WHLBS : Wheelbase
Q : Axle Torque
VA : Ground speed
θ : Angle of implement draft with horizontal

Figure 4.10. Free body diagram of a 2WD tractor

characteristics of the tractor and the forces applied on the system for a 2WD tractor.

The method of calculating the residual parameters is based on moment summation around the rear axle. In this section the relationships among the parameters will be described briefly. Section 6.5 analytically describes the various relationships among the soil, tractive device and tractor design, in the form of equations for 2WD, FWA and 4WD tractors.

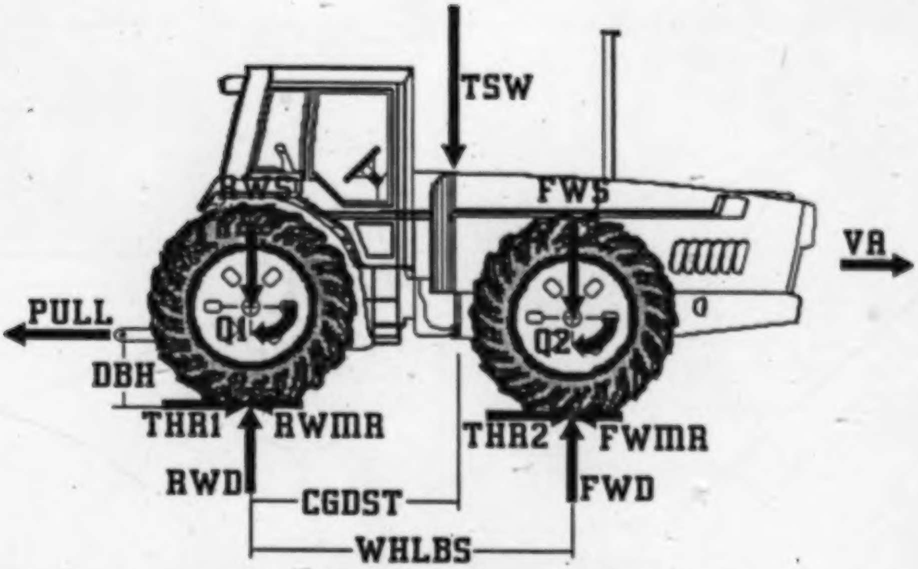
The (gross) thrust of a tractor is proportional to the axle torque and inversely proportional to the tire effective arm.

The motion or rolling resistance force is a composite parameter combining the effects of the tractor weight, the soil bearing capacity, the tire size, the inflation pressure and number of tires. This force is proportional to the tractor weight, the tire pressure and width, and the number of tires, and is inversely proportional to the soil bearing capacity and tire diameter. The motion resistance applies to both powered and unpowered wheels. The powered wheels can overcome their own motion resistance. The unpowered wheels cause a parasitic motion resistance force which must be overcome by the powered wheels. The multi-passing effect applies to FWA and 4WD tractors and describes the decrease in motion resistance of the rear wheels due to the packing of the front wheels.

The drawbar pull is the difference between the thrust and the tractor motion resistance. It is also called net pull and is usually plotted versus slip. The drawbar power is the product of the drawbar pull and the ground speed. According to the previous analysis, the drawbar power increases as the ground speed increases. The drawbar power is a more important parameter than the drawbar pull and provides information about tractor performance. The drawbar pull that is developed is related to the tillage implement draft. Upadhyaya (1984) developed a prediction equation for tillage tool draft using mechanics and dimensional analysis. The draft was estimated as a function of tool width, depth of operation, dynamic cone index (Wismer and Luth, 1972), soil wet bulk density and forward velocity. The equation was found to be valid for both subsoiler and moldboard plow, when static cone index, rather than dynamic cone index was used.

Slip represents the percentage of loss in forward velocity and is affected by the load exerted on the tractive device, the characteristics of the tractive device and the soil strength. The travel ratio represents the ratio of the tractor velocity over the theoretical (no-load) velocity and is expressed as a decimal. The travel ratio is the complement of slip, expressed as a decimal. The theoretical velocity is meaningful for tractive members and is proportional to the engine speed and gear. The actual or ground velocity represents tractor movement in the direction of travel, per unit of time. The actual velocity is proportional to the no-load velocity and inversely proportional to the slip. It is also the factor having the largest effect on the drawbar power. Richardson et al (1983) presented an approach for measuring ground velocity using a dual beam Doppler radar. The radar performance was found to be satisfactory, showing immunity to various sources of noise, like dust and wind speed. The sensor accuracy was found to be dependent on the location of the sensor on the vehicle and by the pitch, yaw and roll motions of the vehicle as it moved across the field. The use of a dual beam radar sensor showed improved performance compared to a single-beam radar unit.

During tractor operation, regardless of load application on the tractor, there is a weight transfer from the front of the tractor to the rear. The amount of weight transfer is a function of the torque applied on the driving wheel, the drawbar pull, the tire effective arm, the drawbar height and the tractor wheelbase. For a 2WD tractor the weight transfer is straightforward. However, for a FWA and 4WD tractor "equivalent" parameters should be developed to "equate" the general vehicle performance to the rear axle. Weight transfer is greater in lower gears, increasing rear axle weight and drawbar pull. Static weight distribution recommendations for a 4WD tractor make clear the concept of the weight transfer. Figure 4.11 shows the same information as Figure 4.10, but for a 4WD tractor.


TSW
RWS
FWS
VA
PULL
Q1
Q2
DBH
THR1
RWMR
THR2
FWMR
RWD
FWD
CGDST
WHLBS

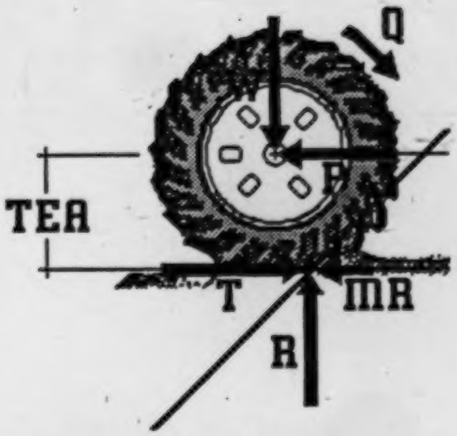
TSW : Tractor Static Weight
RWS : Rear Static Weight
FWS : Front Static Weight
RWD : Rear Dynamic Weight
FWD : Front Dynamic Weight
PULL : Drawbar Pull
DBH : Drawbar Height
THR1,2 : Thrust
FWMR : Front wheel motion resistance
RWMR : Rear wheel motion resistance
CGDST : distance of center of gravity from rear axle
WHLBS : Wheelbase
Q1,2 : Axle Torque
VA : Ground speed

Figure 4.11. Free body diagram of a 4WD tractor

Dynamic front and rear weight are the loads on the front and rear axles respectively, considering weight transfer. The total tractor weight does not change.

The Dynamic Traction Ratio or pull ratio or traction coefficient is the ratio of drawbar pull to dynamic rear load for a 2WD tractor or total tractor weight for a FWA and a 4WD tractor. The Gross Traction Ratio is the ratio of the thrust, exerted by any traction member, over dynamic load, as defined for the DTR. Force efficiency is defined as the ratio of DTR over GTR and determines the fraction of the total force, exerted by the tractor, that is finally useful.

The power coefficient (Persson, 1967) indicates how much output power a wheel with a given vertical load produces when driven with a given rotational speed. The power coefficient determines the utilization of the useful pull as a function of the travel ratio and is equal to the pull ratio times the travel ratio. The Tractive Efficiency is the ratio of output (drawbar) to input (axle) power. It is also expressed as the product of the Force Efficiency and the travel ratio. Bashford (1976) defined the drawbar power to PTO power as tire efficiency and plotted the ratio versus slip. Even though the shape of the tire efficiency curves is the same as Tractive Efficiency curves, the actual values of the tire efficiency are slightly lower than the values of Tractive Efficiency at the same slip level. Figure 4.12 shows the forces applied on a single wheel.



W : Vertical load

Q : Input torque

T : Thrust

MR : Motion resistance

P : Pull

R : Soil reaction

TEA : Tire effective arm

Figure 4.12. Static free body diagram of a single wheel. (Peters, 1984)

### 4.3.3. Tractor field performance prediction

Zoz (1972) presented a study with regard to in-soil tractor performance prediction based on tire performance under average field conditions. The underlying concept was the use of the Nebraska Tractor Test Report data to predict the in-soil tractor performance. As a first step tire performance evaluation tests were carried out since the tire performance is highly dependent on the soil surface condition. Not all possible soil types were tested but the performance tests were of a comparative nature, comparing performance with a tire operating satisfactorily in the field.

Zoz (1972) calculated the tire performance in terms of the Dynamic Traction Ratio (DTR), resulting from a certain weight transfer. The weight transfer calculation was based on the angle and location of the line of draft, with the horizontal component representing drawbar pull. The dynamic weight coefficient was determined as a function of the geometrical tractor characteristics and the draft angle below horizontal. The coefficient incorporated weight transfer from both the implement and the front of the tractor. However, no provision was made for the torque applied on the traction member. DTR was primarily a function of the travel reduction or slip of the drive wheels. Its magnitude was also depended on the tire characteristics.

In order to determine Tractive Efficiency the axle and drawbar power are required. The axle power is converted to a tangential force and a velocity, but not all the power is converted to drawbar power. Tangential force is lost due to motion resistance and forward velocity is lost due to slip, both causing tractive efficiency to be less than one hundred percent.

An important point made by Zoz (1972) is the definition of the zero slip point at the self propelled or zero pull condition. By this definition, tire efficiency, tractive efficiency and dynamic ratio must be zero when travel reduction is zero.

Tire performance as an interfacing factor between tractor capabilities and soil limitations is affected by the slip, the axle torque, the drawbar pull, the front and rear tractor weight, the tire size, the number of tires on the axle, the tire pressure and the soil condition. Slip of the tractive members is the primary independent variable. Optimum drawbar pull is determined from maximum Tractive Efficiency for each soil condition.

By reducing the tire load and pressure, and increasing the tire size and number of tires, the wheel tractive performance can be improved significantly, due to ground contact pressure relief. By increasing the tire size or the number of tires, both tire and tractor performance are improved favorably. Tire performance is proportional to soil strength. Tractive Efficiencies of over 90% may be obtained on a concrete surface, while 50% is difficult to obtain in soft or sandy conditions.

In the determination of tractor performance from tire performance curves, Zoz made use of the tire Tractive Efficiency and the DTR, which are both empirical functions of slip. For a given weight, no-load speed, axle power and weight transfer coefficient a slip value can be calculated and the drawbar pull, the drawbar power and the travel speed can be determined. The solution is a trial and error approach. The exact solution can be obtained directly if the functional relationships between tire efficiency, dynamic ratio and slip are known.

A tractor drawbar performance predictor chart was developed by Zoz (1972), using the equation

$$RWS*SO/(AHP*375)=TE*(DR^{-1}-DWC)/(1-TR/100) \;..........4.11$$

where: $RWS$ = static rear weight (lbs)

$SO$ = no-load travel speed (miles/hr)

$AHP$ = axle power (HP)

$TE$ = tire efficiency (dimensionless)

$DR$ = dynamic ratio (dimensionless)

$DWC$ = dynamic weight coefficient (dimensionless)

$TR$ = travel reduction (dimensionless)

The development and the graphical solution of Zoz's tractor performance predictor chart, along with the computer algorithm, based on the chart, will be described and discussed in detail, in the sixth chapter.

The implement fits in the equation through the weight transfer coefficient under *average* field conditions. The DWC used was 0.65 for mounted implements, 0.45 for semi- mounted implements and 0.25 for towed implements.

The soil in use is classified as firm, tilled and soft. Description of the soil type is given, in order to cover a wide range of soils. However, a range of Cone Index values that designates each soil class, was not presented. In the computer model that will be presented in a subsequent chapter, average values of 1050 kPa, 700 kPa and 350 kPa were assumed as average values for firm, tilled and soft soil, respectively.

A simple graphical predictor was devised by Zoz (1972) for in-soil 2WD tractor performance prediction, as an outgrowth of a computerized iterative process. The purpose of the predictor development was to simplify the process of the in-soil tractor performance parameter prediction, using as inputs readily available information. Drawbar pull calculation was based on rear static weight instead of dynamic values. No-load or advertised speed was used as an entry point to the predictor chart. In the model to be presented the use of the tire effective arm, the computerization of the process and the availability of ground speed information will change the required input parameters, obtained by extrapolating the information from the Nebraska Tractor Test Report and the tractor analysis on concrete.

Figure 4.13 shows various relationships in calculating power distribution throughout the tractor. Two relationships given by Zoz (1972), and not shown in Figure 4.13, are:

Axle Power = 0.96 (PTO Power).......................4.12

Drawbar Power = 0.92 (Axle Power)..................4.13

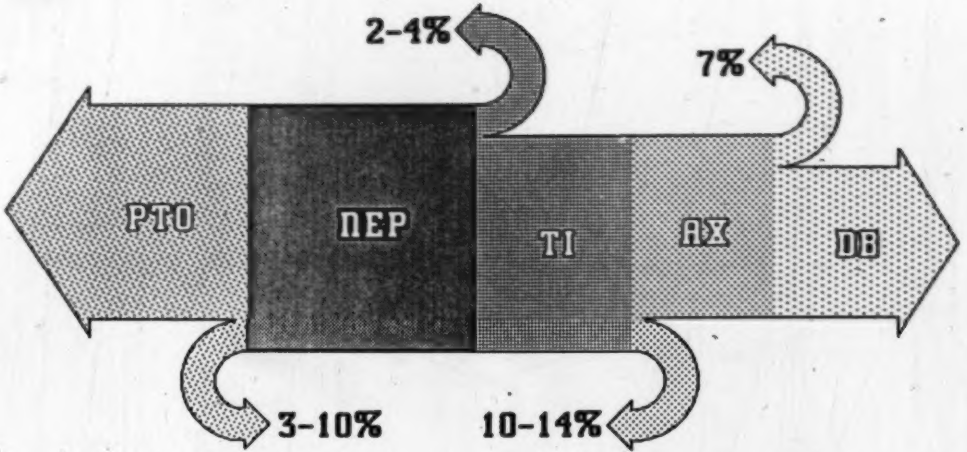
and are used during the tractor analysis on concrete.

### 4.3.4. Further developments

Zoz and Brixius (1979) described equations for in-field tractor performance prediction based on information of tractor performance on concrete. The tractor performance on concrete was reported as a function of the tread bar height, tire manufacturer, tire hardness and age, tire construction (bias or radial ply), dynamic weight (% of the carrying capacity), tire rubber conditioning prior to test, ambient temperature and track cleanliness. Pull Ratio and Drawbar Power to PTO Power ratio were plotted as a function of slip. The similarity of the Drawbar/PTO Power curve with the Tractive Efficiency curve was pointed out. The Pull Ratio was expressed as an exponential function of the wheel slip (S), tire hardness (k), geometrical wheel parameters (b,d) and vertical wheel load (W), in the following equation,

$P/W=1.02\ (1-e^{k(bd/W)S})$ ...........................4.14

The Torque Ratio was described as a function of the Pull Ratio and the motion resistance was defined as 2% of the dynamic tire load. Equation 4.15 describes this


2-4%
7%
PTO
NEP
TI
AX
DB
3-10%
10-14%

PTO : Power Take - Off Power
NEP : Net Engine Power
TI : Transmission Input Power
AX : Axle Power
DB : Drawbar Power
% : Power Losses

Figure 4.13. Power transmission across the tractor

relationship, in which Q represents Torque.

$$Q/rW = 1.02\ (1-e^{k(bd/W)S}) + 0.02 \ldots\ldots\ldots\ldots\ldots\ldots 4.15$$

The Tractive Efficiency was described as the ratio of the Pull Ratio and the Torque Ratio. The influence of the tire was expressed through the tire loading factor, tire hardness and slip. Since the equations were meant to be used for concrete, no provision to include soil properties was made. However, similar equations, reported by Wismer and Luth (1974), had substituted the tire hardness coefficient with the soil Cone Index. While Zoz (1972) determined ratios on a static tire load basis, Zoz and Brixius (1979) used dynamic tire load for the determination of Pull Ratio and Torque Ratio.

Leviticus and Reyes (1983a,b) presented studies with regard to traction on concrete in terms of Dynamic Ratio, Tractive Quotient and Tractive Efficiency. The two studies were a continuation of the work presented by Zoz and Brixius (1979) and the SAE Task Force Final Report (1978). The variables that affect tire performance on a concrete track were classified as tire parameters, track condition, tractor configuration, and size. The analysis was performed on a group of tractors classified according to the power range, the tractor configuration, the number of tires on the drive axle and the tire construction. The Dynamic Ratio and the Tractive Efficiency were presented as generalized equations of the ones presented by Zoz and Brixius (1979). Tractive Quotient was defined as the exponential part of the equations presented by Zoz and Brixius. In order to perform a regression analysis of the Pull Ratio and the Tractive Efficiency on each group of tractors, the equations were given a logarithmic form. In the equations presented by Zoz and Brixius the values of the "maximum dynamic ratio" and the rubber tire hardness were constants. According to this study both parameters varied within each tractor group.

The most important issue reported by the SAE Task Force (1978) was the development of an equation for a bias-ply tire rolling radius prediction. The rolling radius of a tire was given as a function of the unloaded tire radius and the dynamic loaded radius. The dynamic loaded radius was calculated from the static loaded radius and the tire deflection due to weight transfer. The tire deflection was calculated by the tire load-deflection curves. Solving the equation 4.12 for Pull Ratio with the slip as the unknown variable and properly substituting the Pull Ratio by the difference of the Torque Ratio and the motion resistance coefficient, the value of slip was calculated.

Charles and Schuring (1984) presented an equation for predicting the effective rolling radius of agricultural drive tires, as a function of the loaded and the unloaded tire radius, and an empirical constant $k$ determined through experimental procedures. One radial and three bias ply tires were tested under zero drawbar pull. The k values were derived from the statistical analysis of the data. The observed differences were attributed to the differences in tire design.

Brixius and Wismer (1978) studied the role of slip in traction, defining zero conditions. The terms towed wheel (zero torque), self-propelled wheel (zero pull) and driving wheel were defined. At zero torque or zero pull the slip is zero. When pull is developed, some relative motion between the traction element and the supporting medium must occur due to shear forces through strain in the traction member or supporting medium. The most common zero condition is zero pull on a hard surface. Slip was defined as a hard surface performance parameter whereas, travel reduction was defined as a test surface performance parameter. Travel reduction is soil dependent and does not have a fixed basis. Equations describing drawbar pull and tractive efficiency as a function of soil properties (CI), tire dimensions and slip were presented. The equations were:

$$P/W=0.75(1-e^{-0.3*C_n*S}) - (1.2/C_n+0.04) \; \ldots\ldots\ldots\ldots\ldots 4.16$$

$$TE=[1-(1.2/C_n+0.04)/(0.75(1-e^{-0.3*C_n*S}))](1-S) \; \ldots\ldots 4.17$$

The rolling radius does not affect Pull Ratio and Tractive Efficiency, but does affect Torque Ratio and motion resistance. The rolling radius was calculated by the method mentioned previously. However, the measurements concern a hard surface and the tire does not deflect in soil as much as it does on concrete.

Usually tractor performance parameters are plotted versus slip. In order to remove the effect of this factor, the Tractive Efficiency can be plotted versus Pull Ratio.

Adsit and Clark (1983) performed a field study using equations 4.16 and 4.17, to predict in-field 4WD tractor performance as a function of slip, taking into consideration the soil Cone Index values. The researchers found that a traction model based on the Wismer and Luth equations can predict the power-to-weight ratio for various speed and drawbar pull regimes. They also predicted that the ratio will remain constant if the soil surface is firm and if slip is above 10%.

Upadhyaya and Nobari (1984) investigated the soil-low pressure pneumatic tire interaction, modeling the tire material as layered, orthotropic and rubber-fibre composite, and the soil as distributed springs. In the mathematical model that was developed, the inflation pressure, the vertical axle load and the applied torque were included. Further model development is required, before the analysis will be complete.

# 5. COMPUTER MODELS OF PHYSICAL SYSTEMS

## 5.1. What is a computer model?

According to Speckhart and Green (1976), a computer model is the emulation of a physical system using a set of logical relationships, expressed in terms of nontrivial mathematical equations, that govern and describe the behavior of the system.

The concept of the computer model first emerged in large computers, due to the fact that the emulation of a physical system requires the solution of many and complicated relationships, demanding an outstanding capability of number crunching. The complexity of the simulation models has been increasing along with the hardware capabilities and the software support of the computers, as well as the complexity of the contemporary problems and the better understanding of the mechanisms of the physical systems.

The early computer models were written in FORTRAN. The study of the time dependent response of the physical systems caused the development of special purpose simulation models, as opposed to general purpose models developed for design analysis, case study and decision making.

## 5.2. Computer models literature review

The computer models extend to a wide range of applications, and they are divided into two groups that are of particular interest in agricultural engineering.

The first group of applications concerns general purpose models relevant to farm management and decision making, based on efficiencies or tractor-implement-farm size matching.

Colvin et al (1984) presented a menu driven interactive computer simulation model, named TERMS, in order to predict field capacity and fuel use for a specific field operation and crop. An important feature was the use of a data library containing field, implement and tractor information. The inputs are machinery design specifications, operating conditions and costs. The outputs concern machinery operation and field statistics, and operating costs. The simulation technique used segmentation of the field into cells and calculation of the cell parameters, which at the end of the day were pooled.

Buck et al (1984) presented a general purpose simulation model for analyzing different mobile machinery operations. The model was written in FORTRAN for an IBM System/370 and involved an input/output program and a simulation program, using the simulation software package called SLAM and FORTRAN subroutines to adjust the program to the system being simulated. The input information concerned the equipment to be used, the field layout and the tasks to be performed. Each piece of machinery was treated as a "black box" with certain attributes. The field was represented by a set of locations at which tasks were performed or materials were stored. The model calculated the time required to complete a task, the distance or area covered, the draft and the PTO power required, the energy required and the fuel consumed. The major drawback of the application was that user programming was required to match the model with the system to be simulated.

The second group of applications refers to engineering models that are relevant to tractor design, traction devices, soil behavior and their interaction. These models are mainly to predict tractor performance.

Smith et al (1982) presented an engineering design oriented application integrating three computer programs. Two of the programs, DRAM and ADAMS, were simulation models applicable to two-dimensional and three-dimensional analysis of mechanisms and vehicle dynamics, respectively. The DRAM and ADAMS simulation models used a mnemonic coded language to input parameters and provided solutions to static, dynamic, kinematic or design problems (interference). The third program, named HAL, was a graphics package for drawing static colored three-dimensional images and performing animations, to illustrate the operation of the proposed design. Postprocessors facilitated the display of the results using a screen refreshing terminal. The simulation of mechanisms and vehicle dynamics using images eliminated the need to build some initial prototypes of a new machine.

Peters (1983), in analyzing the weight transfer on four wheel drive tractors, developed a user-oriented interactive software for prediction and investigation of dynamic force reactions on the tractor. Twelve tractor parameters were calculated, providing values for any two of them. The tractor parameters concerned lengths, forces, torques, ratios and efficiencies. The major equation of the model is the weight transfer prediction, based on moment summation around the rear axle.

McLaren et al (1983), using standard performance equations and providing input parameters relative to tractor design, soil strength, angle of drawbar pull, and vehicle traction ratio, predicted in-field tractor performance and tractor longitudinal stability. The tractor performance was expressed in terms of ratios and efficiencies, which were plotted on a performance versus slip diagram. The model was extended to include angle of sideslope and "effective" tractor performance parameters were calculated taking into account the storage of potential energy when the tractor was moving uphill. The stability of the tractor against overturn was estimated by calculating the critical front dynamic load ratio.

Summers (1983), Summers and Von Bargen (1983) and Summers et al (1983), presented a CSMP simulation model to predict gross vehicle motion and drive train motions for 2WD and 4WD tractors. The model simulated the operation of the tractor engine, the power train and the final drive, and was used to analyze a new tractor power transmission design. The engine operation was simulated by an engine torque-speed relationship. The power train and the final drive were simulated by lumped masses connected by torsional springs, transmitting torque and subjected to angular motion. Simulated forward velocity, wheel slippage and engine speed were compared to measured data. Soil variability was included in the model using a standard pattern of soil conditions. The predicted values correlated well with the experimental data.

Witney (1983), using empirical relationships, attempted to predict the required power level and match a tractor with an implement for a particular machinery operation on a specific soil. The relationships referred to soil moisture, soil properties, plow draft, mobility number, soil damage penalty, available and required workdays, soil aggregate breakdown, crop timeliness penalties and power and machinery costs. The use of a nomograph, named "Ploughing Performance Predictor", helped in calculating draft developed by a plow in order to estimate required drawbar power. Built-in logic allowed the elimination of non-feasible or non-reasonable solutions.

Sudduth (1984) presented an application-oriented computer program for three-point hitch design and evaluation, named Interactive Hitch Design and Analysis

System. The system was capable of displaying outputs both in tabular and graphics format using a two-screen function. The outputs included listing of input data, lift capacity, mechanical disadvantages of the design, line of pull, linear and angular motions of moving parts, loads on the hitch due to forces and inertial effects, implement attitude (pitch, roll and yaw), forces and pressures induced by the implement and weight transfer. Input data were supplied to the program either from the user through the keyboard or from a predefined database file. The program used three separate data files providing information about the hitch and the tractor design, the implement and the quick-coupler. An important feature of the program was the use of two-dimensional equations for three-dimensional analysis of the implement hitch.

Kline and Perumpral (1984) developed a computer model to predict the vertical soil stress distribution, caused by the wheel-soil interface, integrating point loads over the contact area. The model was based on Boussinesq's stress distribution theory. Wheel-soil contact area shape and magnitude, dynamic load and soil concentration factor were calculated.

## 5.3. Tractor analysis computer models

In all the engineering disciplines the use of computer models tends to be a common practice in predicting a system's behavior. In agricultural engineering the system can be the tractor, the implement, the soil, an irrigation technique, a heat transfer system or a control system. Power and machinery, as a field within agricultural engineering, is interested mainly in tractor performance, based on tractor, tire and soil information.

The tractor performance computer models are divided into two major categories, according to the subject of study. The first category considers the tractor as a system or "black box", determining tractor performance in terms of global parameters, like powers, forces, ratios or efficiencies. The second category considers the tractor as an assembly of systems, cooperating within the tractor's power train, defined as a series of axles and clutches or gear trains, which in turn are defined as lumped masses connected by massless torsional springs. The performance of the systems is measured in terms of tractor performance.

These approaches to tractor analysis can be defined as macroanalysis and microanalysis respectively. The macroanalysis considers the tractor performance from the user's point of view. In contrast, the microanalysis examines the interactions inside the tractor from the designer's point of view. In both cases, a major problem in developing a realistic model of tractor performance is the description of the tractor-soil interface.

Soil modeling can be implemented either by a set of soil parameters at discrete stages or by an empirical equation involving various soil parameters and fitting constants. In most cases the first option is selected since satisfactory models do not exist for describing the soil as a deformable body.

The computer models can be divided into two major categories according to the approach to analyze the system. The first category refers to deterministic models which use mathematical and logical relationships to calculate values for system parameters using direct or iterative procedures, when values for input parameters are specified. In deterministic models the results are dependent on parameters other than time. The second category refers to simulation models, which predict the system's dynamic response over time to various external stimuli.

Deterministic models are usually written in high level languages, like BASIC or FORTRAN, providing a significant Input/Output (I/O) capability. Some models support extensive database, containing parameters required for the solution procedures. An important feature of the models can be their ability to cooperate with other models written in different programming languages, since various languages are designed for handling different processes.

Two-dimensional and three-dimensional Finite Element Analysis (FEA) is a procedure used by deterministic models in various applications of agricultural engineering. Davis and Cooke (1983) presented a friendly or easy-to-learn-and-use computer software to perform Finite Element Analysis.

Upadhyaya et al (1984), presented a Finite Element Model concerning prediction of the tractive ability of pneumatic tires.

The development of simulation models is assisted by the use of simulation oriented computer languages, like CSMP[1], which is a FORTRAN based computer language, and GPSS[2]. Initial and terminal conditions, as well as time dependent functions, are important features of these languages, enabling the simulation of a system's transient response with ease.

The use of computerized images (graphics) is an important accessory of computer models. Computer Aided Design (CAD) uses graphics techniques extensively, facilitating the easy design and analysis of new concepts, both in mechanics and electronics. Digital Image Processing (DIP) supplemented by digital mathematics, enable the pictorial representation of physical systems (Pits, 1984).

Model generalization, using redefinable parameters through an interactive operation, is important. Programming skills, software support, and hardware advantages and limitations, are important factors for program reliability, understandability and user friendliness. In addition a database can make easily accessible and managable a large database. Program interaction can be crucial during information processing.

---

1. CSMP: Continuous System Modeling Program.
2. GPSS: General Purpose Simulation System.

## 5.4. Pros and cons of computer models

Up-to-date technology in agricultural engineering offers many alternatives through a number of feasible combinations. In order to select the optimum solution in farming operations, an analysis of various machinery, implement and soil combinations is required using a trial and error method. This approach is usually costly and time consuming. A computer model attempts to predict how a piece of machinery would or should behave under various conditions. The analysis and the emulation of a system using different strategies can be of significant importance for primary elimination of non-feasible or non-profitable solutions.

The pros, supporting the development and use of a computer model, are the following:

a. by using a computer model the required time, money, equipment and trained personnel is less than that of an actual experiment;

b. an experiment is limited by the available hardware (tractors, implements, tires, data acquisition systems), whereas a computer model is not;

c. the artificial environment generated by the model can establish a firm basis of comparison among different designs or different strategies, freeing the study from the effects of the environmental randomness or "noise";

d. simulation satisfies the need for a measure or indication of a design performance under several circumstances, prior to the manufacturing of the design.

On the other hand the cons in developing and using a computer model, are the following:

a. the computer model complexity and ability to access and process information are largely dependent on computer execution power, operating system capabilities, software support and operating cost;
b. the results from a computer model are unreliable until they are verified by an experiment, since the development of a computer model is based on certain assumptions, affecting the validity of the model;
c. the equations used in a model are valid only within a specified range of values for input parameters.

A model can do only what an engineer would be able to do, but it will perform the task much faster and with more degrees of freedom, using more complex computational algorithms. However, if the underlying mechanisms of a physical system are not well defined, the use of a computer model is meaningless. In tractor performance, the major problem in terms of mechanism understanding and evaluation remains in defining the soil-traction device interaction when soil is considered a deformable body.

### 5.5. Why use a microcomputer

Three factors that encouraged the transition from the large mainframes to the microcomputer domain were the operating costs associated with repeated running of the computer models on mainframes, the inability of most terminals connected to mainframes to display digital images and the dependency of the application on the availability or compatibility of the mainframe operating system. On the other hand, microcomputers are slower and not very well supported in terms of both hardware and software compared to large computers. However, the operating system of most microcomputers is transparent, allowing user interaction that is not possible on mainframe systems. As well, the proper use of the microcomputer operating system can considerably improve the application performance. Recent developments in the microelectronics area and improvements in software support for microcomputers have opened new horizons in the processing of information.

In order to design a computer model on a microcomputer, several factors relative to the available hardware and software should be taken into consideration. Four attributes for deciding in favor of a microcomputer, that were also design goals, were:

a. portability,

b. Universality,

c. interactive operation, and

d. integration.

Portability is defined as the ability to transport physically a machine readable copy of the computer program on an easily transferable media between computer systems. Universality is associated with the ability of the computer program to operate on several computer systems that have common characteristics in terms of the hardware and the associated operating system. Interactive operation is defined as the ability of the user to guide the procedures or select the data used during application execution. The concept of an integrated software is defined in terms of unified structure, multitasking ability and sharing of information (Lu, 1984), in a way that enhances the computer model usefulness.

Structurally the model for this project was designed to be a single disk, complete application package using a popular operating system installed in a broadly used micro computer. An important factor in using a microcomputer based model is the selection of the programming language to implement the application. The Advanced BASIC V2.1, by Microsoft Inc. (1982), provided a flexible language capable of handling keyboard, screen, disk access and printing operations. In addition, the language included commands that could control graphics displays. The four characteristics listed above, are completely satisfied using the MS-DOS operating system on the IBM Personal Computer (PC). An added advantage is that the same operating system is used by many

IBM PC compatible microcomputers, thus enabling a model developed for an IBM·PC to run on microcomputers manufactured by other companies.

The major advantages in using an IBM PC, as opposed to using the University of Alberta's Amdahl mainframe system, is application integration and portability. The major disadvantages are reduced numerical accuracy for complex operations and the lack of extensive computer language support. Since several complex mathematical algorithms available in specialized languages (e.g. APL[3]), had to be programmed in BASIC on the IBM PC for this application.

### 5.6. The operating system

The disk operating system (DOS) is a program that controls all the computer functions and makes it possible for other system and application programs to work (Wolkerton, 1984). The IBM PC uses the MS-DOS (Disk Operating System) by Microsoft Inc. Detail information about the operating system is available in the IBM Disk Operating System (1983) manual. The latest available version of MS-DOS, is V2.1.

### 5.7. BASIC

The Beginners All-purpose Symbolic Instruction Code

---

[3] A Programming Language

(BASIC) is a high level computer language which is neither basic nor for beginners anymore.

Programs written in BASIC can be executed under the control of the operating system using a BASIC interpreter or by compiling the program into object code that contains the machine language code.

The BASIC Interpreter is a link between the application and the operating system. Each program statement is translated into a sequence of machine language operation codes and operands, which are directed to the operating system for immediate execution before the next statement is translated. Program execution is slow, due to the time required for the Interpreter to translate the statement and execute the task.

The limitation of the IBM PC Microsoft BASIC is that the Interpreter workspace is logically limited to 64 K of memory. The ability of the Interpreter to trace program execution and inform the user explicitly about the source of error is very important for program development and debugging.

A BASIC Compiler is available to convert a BASIC program into machine code. The compiler performs the translation phase in one step without the execution phase. Thus the application becomes independent of the high level language as the object code is a collection of machine language statements. The advantages in compiling a program are the elimination of the logical memory restrictions and the increased speed of program execution. More extensive information about BASIC(A) can be found in the IBM BASIC (1983) manual.

### 5.8. Database Management

The integrated software presented in the following chapter is essentially a database management system designed specifically for analyzing tractor performance. Cook (1984) defined the keywords *Database, Database management system (DBMS), File, Record, Field and File manager* and these are the basis of the discussion in the next chapters.

The three most common database management systems and their pros and cons, are:

a. Relational. A relational database consists of horizontal row records in an arbitrary order of rows. The database is easily modified, but long access times required to recover data.

b. Hierarchical. The hierarchical databases orders the data items according to a specified hierarchy of attributes, creating logical links between related data items. Information searches are fast, but additions and deletions to the database must take into account their effects on the lines of connection.

c. Network. The network database allows for more complex links between data records, including lateral connections between related items and many to one links, in which several high-level items point to a common lower-level item. Modifications to this type of database can be even more complex than for the hierarchical database but the sharing of some items can reduce storage requirements.

The hierarchical model is essentially a tree-structured scheme, in which high-order pieces of information are linked through branches to lower-order attributes. This type of database is characterized by the one-to-many linkages between data files. The computer model for this project used a hierarchical database for storing information on floppy disks. The levels of the tree-structure for the database consists of the tractor type, the unit system and the particular design data element grouping. Both records and fields can be randomly accessed in the database.

# 6. TRACTOR ANALYSIS ON CONCRETE AND IN-SOIL TRACTOR PERFORMANCE PREDICTION

## 6.1. Introduction

The integrated software package, that was developed for tractor analysis and prediction, included a tractor analysis on concrete and three in-soil tractor performance prediction models. The three models were titled ASAE D230.4, OECD (Organization for Economic Cooperation and Development), and HELLAS (High Efficiency Localized Locomotive Analysis-Simulation Software), respectively.

In developing the models, the major assumption was *the consideration of the tractor as a "black box", which at a specific engine speed and gear will deliver to the final drive the same amount of power, regardless of soil conditions or other environmental variable conditions.*

## 6.2. On concrete tractor analysis input and output

The tractor analysis on concrete calculates the characteristics of the tractor as a "black box", using well established tractor mechanics and actual data on concrete surface. During the analysis both soil and implement factors were disregarded.

For the tractor analysis on concrete the inputs were:

a. tractor database files including tractor design information and the drawbar performance test, provided by the Nebraska Tractor Test Report (NTTR);

b. tire database files including information provided by two tire companies (GOODYEAR, BFGoodrich).

The tractor information concerned the following parameters:

a. tractor design parameters
  - static front, rear and total weight;
  - drawbar height and wheelbase;
  - distance of center of gravity from rear axle;
  - rated engine speed and PTO power;

b. tractor performance parameters
  - gear setting;
  - engine speed in gear N;
  - drawbar pull and power in gear N;
  - ground velocity in gear N;
  - slip in gear N.

The tire information included the following parameters:

- tire size;
- tire ply rating;
- tire pressure;
- number of tires;
- tire loaded radius;
- tire overall diameter;

  - tire width;
  - maximum load for specific ply and pressure.

The output provided information for twenty one tractor and tire design parameters, and twenty two tractor performance parameters.

The output, in addition to the input parameters, provided information concerning:

a. pertinent tractor parameters in gear N
  - PTO power;
  - axle power and axle torque.

b. tractor performance parameters in gear N
  - gross thrust;
  - theoretical velocity;
  - travel ratio;
  - dynamic traction or pull ratio;
  - gross traction or torque ratio;
  - force efficiency;
  - power coefficient;
  - tractive efficiency;
  - dynamic front and rear weight;
  - calculated weight transfer.

c. tire related information
  - front and rear tire loading factor;
  - tire effective arm.

d. tire-soil interface parameters
  - motion or rolling resistance coefficient;
  - motion or rolling resistance.

## 6.3. Tractor analysis algorithm

Depending on the type of the tractor being analyzed, two different paths were followed for the calculation of the derived tractor performance parameters on concrete. Table B.2 in Appendix B, presents the nomenclature of the variables. The subscript i represents an array.

The first path concerned 2WD and FWA (with the assist disengaged) tractors. The equations involved in the first path, were the following:

a. approximation of the calculated weight transfer

$TCWTR1_i = PULL_i * TDBH/(WHLBS*UCF)$ ............................6.1

b. calculation of the weight transfer

$TCWTR2_i = (TORQUE_i - PULL_i * (TEA_i - TDBH) - RRCF*TDFWT_i*(TEA_i - TRF))/(WHLBS*UCF)$ .............6.2

c. calculation of the Dynamic Traction Ratio

$TDTR_i = PULL_i/(TDRWT_i*UCF)$ ..................................6.3

d. calculation of the Gross Traction Ratio

$TGTR_i = THRUST_i/(TDRWT_i*UCF)$ ................................6.4

e. calculation of the Force Efficiency

$TFCEFF_i = TDTR_i/TGTR_i$ .......................................6.5

f. calculation of the Travel Ratio

$TRRT_i = 1-(SLIP_i/100)$ ........................................6.6

g. calculation of the theoretical speed

$V_i = VA_i/TRRT_i$ ..............................................6.7

h. calculation of the Tractive Efficiency

$TREFF_i = TFCEFF_i*TRRT_i$ .......................................6.8

i. calculation of the axle input power

$TAXPWR_i = THRUST_i*V_i/3.6$ ........................................6.9

j. calculation of the PTO power

$PTOPWR_i = TAXPWR_i/0.96$ ........................................6.10

The coefficient 0.96 represents the Axle Power/PTO Power ratio according to Zoz (1972) and Domier and Willans (1979). The PTO calculation is not involved during the in-soil tractor performance prediction and is used only as an approximate control of the axle power.

k. calculation of the power coefficient

$PWREFF_i = TDTR_i*TRRT_i$ ........................................6.11

l. calculation of front and rear tire loading

$PLDF = SFWT*IPF*100/(NUMF*LDF*PF)$ ........................6.12

$PLDR = SRWT*IPR*100/(NUMR*LDR*PR)$ ........................6.13

Equations 6.14 to 6.24 formed a subroutine which was called after equations 6.1 and 6.2. The equations of the subroutine were the following:

m. calculation of the dynamic rear weight

$TDRWT_i = SRWT+TCWTR2_i$ ........................................6.14

n. calculation of the dynamic front weight

$TDFWT_i = STOTL-TDRWT_i$ ........................................6.15

o. calculation of the total motion resistance

$RRTOTL_i = (RRCR*TDRWT_i+RRCF*TDFWT_i)*UCF$ ...................6.16

Figures 6.1 and 6.2, given by Inns and Kilgour (1978), show the effect of tire size and inflation pressure on the rolling resistance coefficient. For the purposes of the model the graphs were digitized and the best fit equations

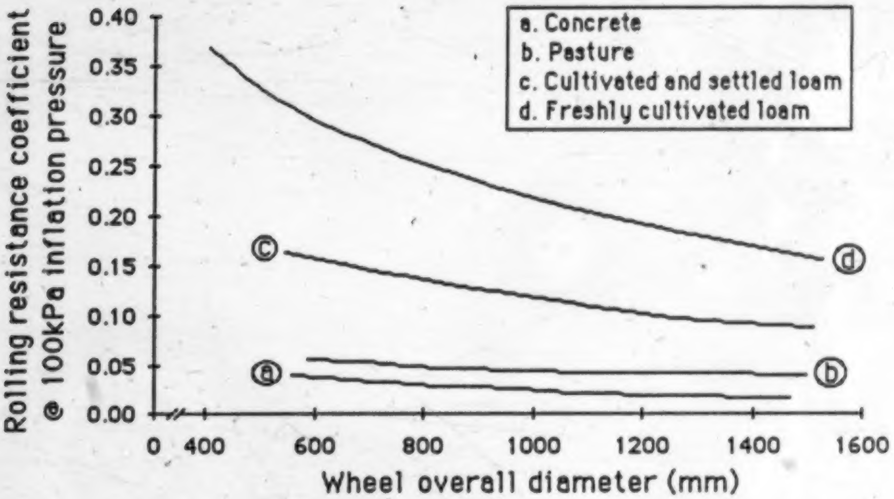


Figure 6.1. Effect of wheel diameter on the coefficient of rolling resistance. (Inns and Kilgour, 1974)

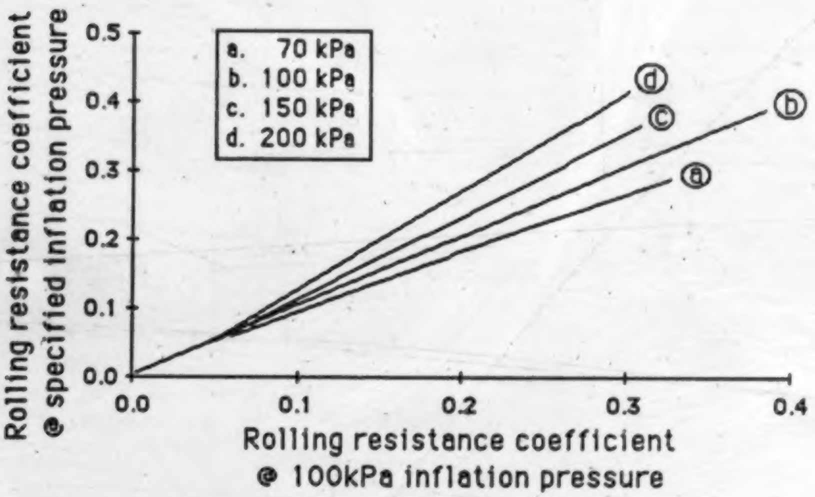


Figure 6.2. Effect of pressure on the coefficient of rolling resistance. (Inns and Kilgour, 1974)

were used in the program. The resultant equations are presented in Appendix B, Table B.6.

p. calculation of the gross thrust

$THRUST_i = PULL_i + RRTOTL_i$ ..................................6.17

q. calculation of the tire effective arm

$TEA_i = (TDR/2) - (TDRWT_i * PHI1) - .3 * SCONV$ ....................6.18

Figure 6.3 presents a sample load-deflection curve, courtesy of BFGoodrich, showing the linearity of the relationship above a certain value of tire load. The intercept of the linear equation is assumed to be 7.5 mm (0.3 inches). This figure is empirical and represents an average value of the intercepts measured on various curves, ranging from 5 to 10 mm. The slope of the linear relationship for rated conditions is estimated using the equation:

$\tan\phi = (X_2 - X_1)/load_{max}$ ..................................6.19

where: $X_1 = 0.3 * SCONV$

$X_2 =$ (overall diameter)/2-(loaded radius)

SCONV=0.0254 (SI) or 1.0 (english)

Correction of the load-deflection curve is required if the tire inflation pressure is different than the rated. Equation 6.20 describes the slope of the curve, taking into consideration the tire inflation pressure.

$TANPHI(R1,R2,R3,I4,I5) = (R1/2 - R2 - 0.3 * SCONV) * R3/(I4 * I5)$..6.20

where: R1=tire diameter

R2=tire loaded radius

R3=tire inflation pressure

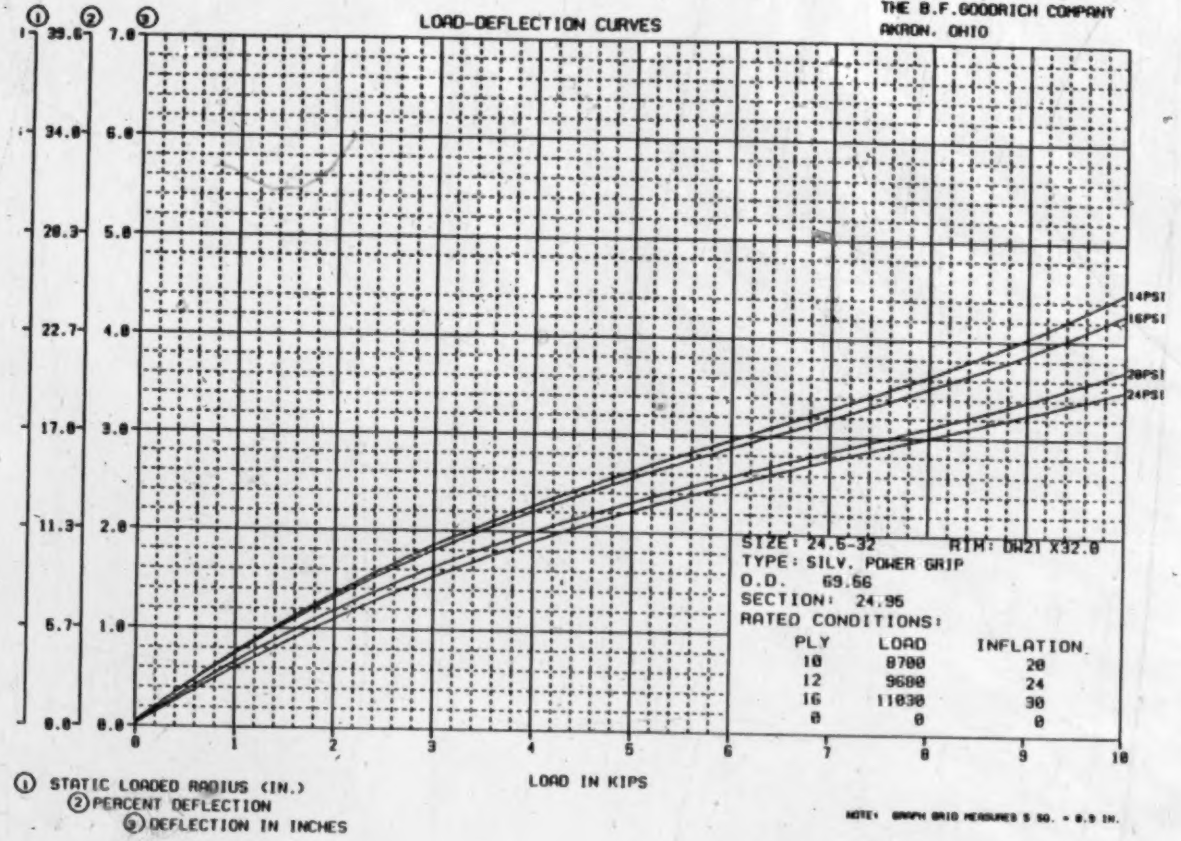


Figure 6.3. Sample load-deflection curve.

(Courtesy of BFGoodrich)

I4=rated load

I5=rated inflation pressure

Equations 6.21 and 6.22 express equation 6.20 in a parametric format, as this is used in the computer program.

PHI1= FN TANPHI(TDR,TRR,PR,LDR,IPR)....................6.21

PHI2= FN TANPHI(TDF,TRF,PF,LDF,IPF)....................6.22

where: PHI1=slope of the linear relationship for rear tires

PHI2=slope of the linear relationship for front tires

The deflection of the tire, for loads within the linearity limits of the curve and for rated inflation pressure, is given by the relationship:

$(\text{deflection})_i=\delta=(\text{load})_i*\tan\phi-0.3*\text{SCONV}$ .................6.23

r. calculation of the axle input torque

$\text{TORQUE}_i=\text{THRUST}_i*\text{TEA}_i$..................................6.24

All of the above equations were involved in an iterative procedure. The number of iterations was equal to the number of observations. Equations 6.12 and 6.13 were an exception, since they were executed once.

The second path for the calculation of the derived tractor performance parameters concerned 4WD and FWA (with the assist engaged) tractors. A number of equations were modified to account for differences in tractor mechanics and these equations are:

a. calculation of a tire loading parameters

PRMTR1= (IPF/(LDF*PF)+IPR/(LDR*PR))*50..................6.25

PRMTR2= (NUMF+NUMR)/2...................................6.26

b. calculation of front and rear tire loading

$$\mathrm{PLDF} = \mathrm{PRMTR1} * \mathrm{SFWT}/(\mathrm{PRMTR2}-(\mathrm{PRMTR2}\ \mathrm{MOD}\ 2)) \tag{6.27}$$

$$\mathrm{PLDR} = \mathrm{PRMTR1} * \mathrm{SRWT}/(\mathrm{PRMTR2}+(\mathrm{PRMTR2}\ \mathrm{MOD}\ 2)) \tag{6.28}$$

c. calculation of the Dynamic Traction Ratio

$$\mathrm{TDTR}_i = \mathrm{PULL}_i/(\mathrm{STOWT} * \mathrm{UCF}) \tag{6.29}$$

d. calculation of the Gross Traction Ratio

$$\mathrm{TGTR}_i = \mathrm{THRUST}_i/(\mathrm{STOWT} * \mathrm{UCF}) \tag{6.30}$$

e. calculation of the axle input power

$$\mathrm{TAXPWR}_i = (\mathrm{THRUST}_i/2) * V_i/3.6 \tag{6.31}$$

f. calculation of the PTO power

$$\mathrm{PTOPWR}_i = 2 * \mathrm{TAXPWR}_i/0.96 \tag{6.32}$$

The equations of the subroutine that were different from the ones already presented, are the following:

g. calculation of the tire effective arm

$$\mathrm{TEA}_i = ((\mathrm{TDF}/2)-\mathrm{TDFWT}_i * \mathrm{PHI2}+(\mathrm{TDR}/2)-\mathrm{TDRWT}_i * \mathrm{PHI1})/2- -(.3 * \mathrm{SCONV}) \tag{6.33}$$

h. calculation of the axle input torque

$$\mathrm{TORQUE}_i = \mathrm{THRUST}_i * \mathrm{TEA}_i/2 \tag{6.34}$$

Equations 6.1 to 6.34 are independent of a unit system due to the coefficient UCF, which was included to compensate for the difference between force and mass. The value of the coefficient was 0.00981 for SI units and 1.0 for English units.

### 6.4. Models input and output

The in-soil tractor performance prediction models used the pertinent tractor performance information from the analysis on concrete as input parameters. The input information for the in-soil tractor performance prediction models included:

a. tractor information;

b. tire information;

c. soil strength, associated with the soil type and expressed in terms of the soil Cone Index value;

d. implement hitch type, affecting all the weight transfer related parameters.

The tractor input parameters to the models, based on the "black box" concept, were:

- gear setting;
- engine RPM in gear N;
- PTO power in gear N;
- axle power in gear N;
- axle torque in gear N;
- theoretical velocity in gear N.

Typical soil Cone Index values were built in the model, and unless otherwise specified, were assumed to be:

- 1050 kPa for Firm soil;
- 700 kPa for Tilled soil;
- 350 kPa for Soft soil.

The above default Cone Index values could be overridden by the user.

The implement hitch type was introduced through a weight transfer coefficient, being equal to:

- 0.30 for integral implements;
- 0.15 for semi-mounted implements;
- 0.00 for towed implements.

The output information was the same as described in section 6.2.

### 6.5. In-soil tractor performance prediction models

Three in-soil tractor performance prediction models, based on different algorithms, were implemented. The basis for the first model was the ASAE Agricultural Machinery Management Data 230.4 (1984), which was an extension of the work presented by Zoz (1972) and thereafter was adopted by ASAE. The second model was based on a proposal by OECD (1984) for predicting tractor field performance from test data using the Mobility Number and empirical equations. The third model, named High Efficiency Localized Locomotive Analysis-Simulation Software (HELLAS), was based on the Wismer and Luth (1974) equation for Pull Ratio calculation and standard tractor mechanics.

#### 6.5.1. ASAE D230.4 model

The ASAE D230.4 model was the author's first approach for in-soil tractor performance prediction. The underlying concept was the use of the Zoz's nomogram in a computerized procedure.

### 6.5.2. Description of Zoz's graph

The Zoz's (1972) tractor performance predictor chart is composed of three quadrants and is shown in Figure 6.4. The variables on the axes represent the input information that is necessary for a graphical solution and the output information that is provided by the chart.

The inputs are zero-slip (theoretical) velocity, axle power, static rear axle force, type of soil and type of implement hitch. The first two parameters are calculated by the tractor analysis algorithm. The static rear axle force is provided by the NTTR. The type of soil and the type of implement hitch are selected by the user, as will be described in the next chapter. The output of the chart provides information concerning slip, ground speed, Dynamic Traction or Pull Ratio and Tractive Efficiency. The procedures of chart development and use are described by Zoz (1972).

### 6.5.3. Implementation and model algorithm

The procedure to determine the equations that describe the curves of the chart comprised the following steps:

a. Accurate copying of the nomogram from the ASAE Standards 1984.

b. Digitizing of the chart.

Figure 6.4. Zoz's chart - ASAE D230.4 (ASAE Standards, 1984) has been removed from the text because of the unavailability of copyright permission.

c. Numerical analysis of the data.

d. Processing of the adjusted data using simple regression analysis to establish the best fit equation.

The equations of the digitized curves are presented in Appendix B, Table B.6. Figure 6.5. shows the flow-chart of the model.

After the complete set of equations was established, the algorithm was implemented following the procedure that is used for the graphical solution of the chart. Before entering the model algorithm the motion resistance and the tire effective arm were calculated. The entry point of the model was the zero-slip or theoretical velocity. Using the logic of the chart the slip was calculated and compared against a limit of 30%. If the slip was higher than this limit, the tractor ballast on the rear wheels was incremented and the slip calculation was repeated. The auto-incrementing of the ballast was limited by the rated tire loading. After the calculation of the slip, the values for Pull Ratio and Tractive Efficiency were determined. All the other tractor performance parameters were calculated using the equations 6.1 to 6.34.

### 6.5.4. Assumptions and limitations

The major assumptions, on which the model was based, are described in the ASAE D230.4.

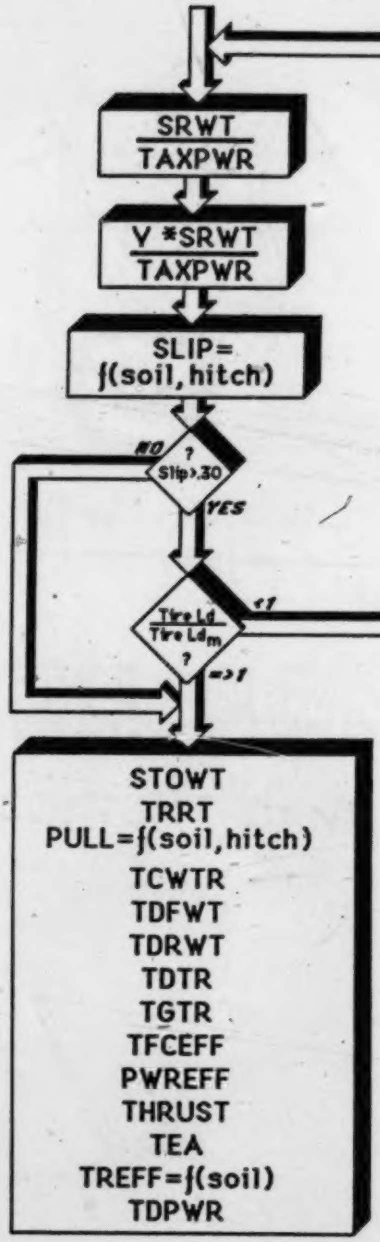

SRWT / TAXPWR
V *SRWT / TAXPWR
SLIP= ∫(soil, hitch)
NO
? Slip>.30
YES
Tire Ld / Tire Ld_m ?
<1
=>1
Increment ballast
STOWT
TRRT
PULL=∫(soil, hitch)
TCWTR
TDFWT
TDRWT
TDTR
TGTR
TFCEFF
PWREFF
THRUST
TEA
TREFF=∫(soil)
TDPWR

Figure 6.5. ASAE D230.4 model flow-chart.

An important limitation of the model is the application to 2WD tractors only. However, the model was tested on the FWA and the 4WD tractors to investigate the results.

Other limitations concern model implementation and scope. A limitation with respect to the model implementation is the accuracy of the digitized curves. Figures C.109-C.110 in Appendix C, show the calibration curves of the models. A limitation with respect to the scope of the model for validity of the results, is the upper limit of slip which confines the model to 30% slip.

### 6.5.5. Discussion

The logic of the model is straightforward. No major modifications were introduced to the model, other than the calculation of the weight transfer within the tractor and the accounting of the weight transfer in the calculation of the forces.

In order to maximize accuracy the process of digitizing was repeated twice, since the results of the first digitizing were not satisfactory. During the second digitizing process various chart statistics, such as origin and scale, were included for each quadrant. Numerical analysis converted the digitized values into real values. The regression analysis was performed on the adjusted values.

The validation of the model can only encompass slip value, Pull Ratio and Tractive Efficiency. All the other equations were selected from the literature and were assembled as required.

### 6.6.1. OECD model

The Organization for Economic Cooperation and Development contributing to the development of standard codes for the official testing of agricultural tractors and protective structures, presented a model (1984) for prediction of tractor field performance from test data. The model was the product of the cooperation of the United Kingdom and France.

### 6.6.2. Model algorithm

The model was based on empirical equations as a function of the Mobility Number (M). The Mobility Number is given by the equation:

$$M=C_n \sqrt{(\delta/h)}/(1+b/2d) \quad \ldots\ldots 6.35$$

where: $C_n$=Wheel Numeric=CI*b*d/W

CI=Cone Index

b=undeflected tire width

d=undeflected tire diameter

W=vertical load on the tire

$\delta$=tire deflection

h=tire section height

The empirical relationships are the following:

$C_{RR}=RR/W= 0.049+(0.287/M)$ ............................6.36

$(C_T)_{max}=T_{max}/W= 0.796-(0.92/M)$ ........................6.37

$k= 4.838+(0.061*M)/(C_T)_{max}$ ...........................6.38

$C_T=T/W= (C_T)_{max}\ (1-e^{-k*S})$ ...........................6.39

$NT= f(C_T)_{rear} + f(C_T)_{front}$ ...........................6.40

$DP= NT-f(RR_{rear})$ .....................................6.41

$T= NT+RR_{rear}+f(RR_{front})$ ...............................6.42

where: $C_{RR}$=coefficient of rolling resistance

$(C_T)_{max}$=maximum coefficient of traction

RR=rolling resistance

$T_{max}$=maximum Thrust

k=parameter

$C_T$=coefficient of traction

NT=Net Traction

DP=Drawbar Pull

T=Thrust

In addition, equations 6.2 and 6.18 provided an estimate of tractor weight transfer and tire effective arm to give the model a dynamic character. The flow-chart of the model is shown in Figure 6.6.

The steps involved in the algorithm were the following:

1. Calculation of the mobility number on the front and rear wheels.
2. Calculation of the rolling resistance on the front and rear wheels using the rolling resistance coefficient.

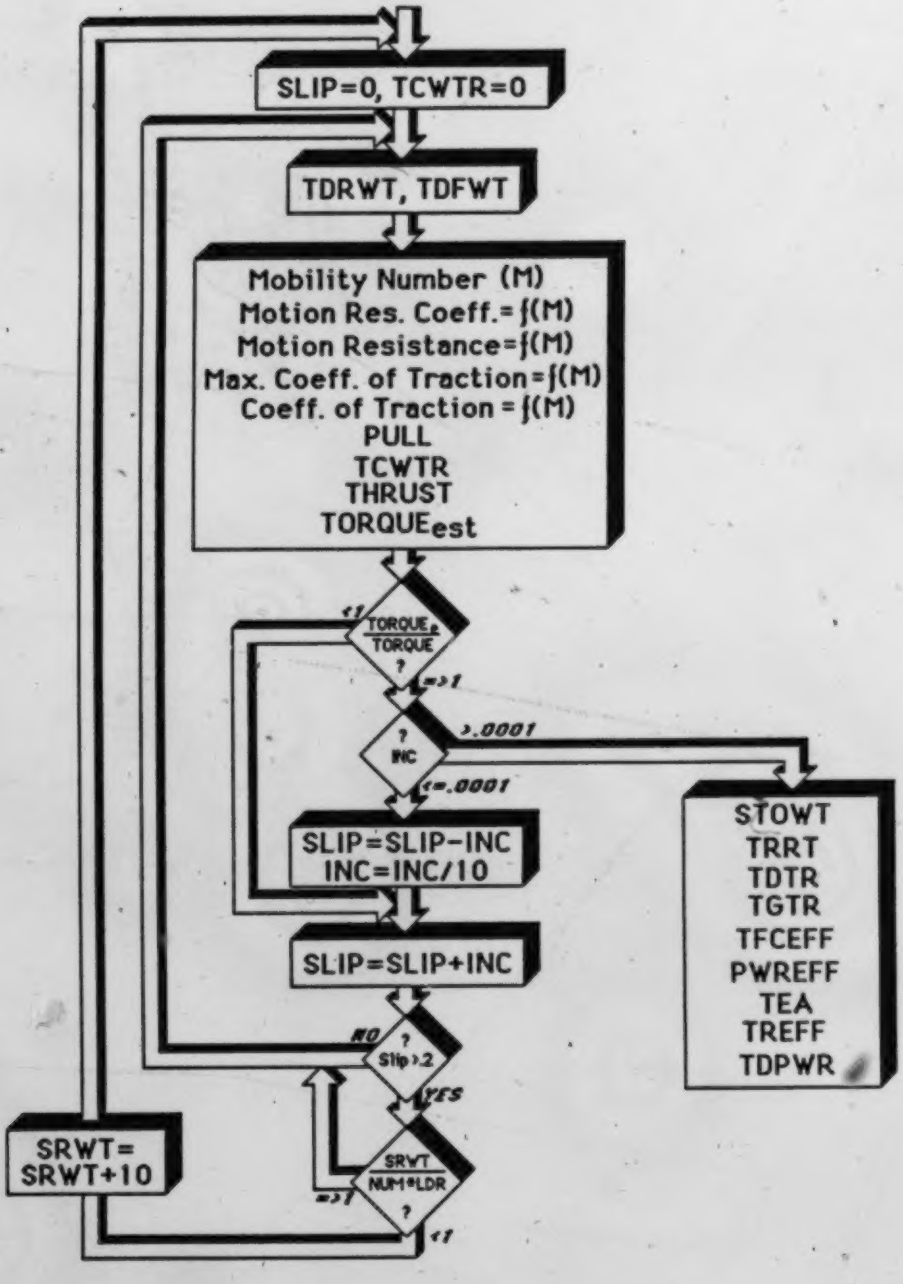

SLIP=0, TCWTR=0
TDRWT, TDFWT
Mobility Number (M)
Motion Res. Coeff.=f(M)
Motion Resistance=f(M)
Max. Coeff. of Traction=f(M)
Coeff. of Traction = f(M)
PULL
TCWTR
THRUST
TORQUEest
TORQUEe / TORQUE ?
<1
=>1
? INC
>.0001
<=.0001
STOWT
TRRT
TDTR
TGTR
TFCEFF
PWREFF
TEA
TREFF
TDPWR
SLIP=SLIP-INC
INC=INC/10
SLIP=SLIP+INC
NO
? Slip>.2
YES
SRWT / NUM*LDR ?
=>1
<1
SRWT=
SRWT+10

Figure 6.6. OECD model flow-chart.

3. Calculation of the maximum coefficient of traction.
4. Calculation of the parameter k.
5. Calculation of the coefficient of traction for a slip value.
6. Calculation of the Pull for the slip value.
7. Calculation of the Thrust for the slip value.
8. Calculation of the axle Torque based on the Thrust.
9. Compare calculated and known axle Torque.
10. If calculated Torque is less than known axle Torque then increment slip, go to 11 or else go to 12.
11. If slip is less than or equal to 20% then go to 6 or else reset slip, increment ballast and go to 1.
12. Calculation of tractor performance parameters.

### 6.6.3. Assumptions

The OECD Tractor Tests are carried out on concrete, like the Nebraska Tractor Tests, for standardization purposes. The empirical equations as a function of Mobility Number were established after a very large number of tests with a range of agricultural tires in many different field conditions over a number of years.

The note by the OECD Secretariat mentioned two assumptions. According to the first assumption, if the tractor is operated with an integral implement, it may be assumed that the weight of the implement replaces some of the ballast used in the test. According to the second assumption, the Drawbar Pull of an implement is applied very nearly at the ground level; therefore, it may be assumed that the vertical load exerted on the tires is independent of the magnitude of the Drawbar Pull. Apparently OECD over-simplified the effect of weight transfer to the rear axle from the implement due to the exerted Drawbar Pull, in order to avoid extra complications.

The original model used tractor engine torque and transmission ratios to calculate the available torque at the axle. The model, based on the "black box" concept, assumed the torque at the axle as calculated during tractor analysis, and disregarded the engine power and the power losses across the tractor power train.

The OECD original proposal assumed the use of the tire static loaded radius in the equations calculating moments around the rear axle. The model calculated the tire effective arm taking into consideration tire deflection.

### 6.6.4. Limitations

The predictive method was based on the presented empirical relationships between tractive performance parameters, tire information and soil strength.

An important limitation is the nature of the model. The empirical equations of the original model were based on static loads. The model that is presented, was modified to account for weight transfer, changing the load distribution across the tractor and making doubtful the validity of the empirical equations for the new operating conditions.

### 6.6.5. Discussion

The OECD is an all-tractor performance prediction model, using tractor information on concrete and empirical equations describing tractor mechanics. The original model provided exact solutions but was based on static relationships rather than dynamic ones, assuming the static axle load from the Tractor Test Report. The model was modified by the author to account for weight transfer through an iterative procedure, taking into consideration not only the exerted drawbar pull but also the torque applied on the tractive devices.

A conceptual problem of the original model presented by OECD was the use of static weight in the calculation of the Mobility Number. The computer model that is presented in this study accounts for weight transfer, increasing the magnitude of the load applied on the rear wheels and decreasing the magnitude of the load applied on the front wheels. The increased load on the rear wheels caused a decrease of the Mobility Number, which in turn caused an increase in the rolling resistance and the drawbar pull, therefore the Thrust. Since the Torque is calculated as the product of the Thrust and the tire effective arm, it is obvious that the calculated and the known Torque, at step 10 of the algorithm, are balancing at very low slip values. The dependency of the original model on static weight was proven to be a great problem.

The accuracy of the results at this stage can not be determined, however, the fact that certain forces and dimensions were over-simplified during the development of the empirical equations raises certain questions about the accuracy of the model.

In addition, there is no way to validate the modified OECD model with respect to the original model, since at this stage the two models are different in principle.

### 6.7.1. HELLAS model

The High Efficiency Localized Locomotive Analysis-Simulation Software (HELLAS) is a model based on the Wismer and Luth (1974) equation for Pull Ratio and well established tractor mechanics. The equations of the model were made available through the literature and were presented during the tractor analysis algorithm description. The flow-chart of the model is shown in Figure 6.7.

The results of the prediction model were obtained through an iterative procedure. The independent variable was the slip, which was incremented in variable steps. The incrementing of the ballast was a function of the slip and the rated tire loading.

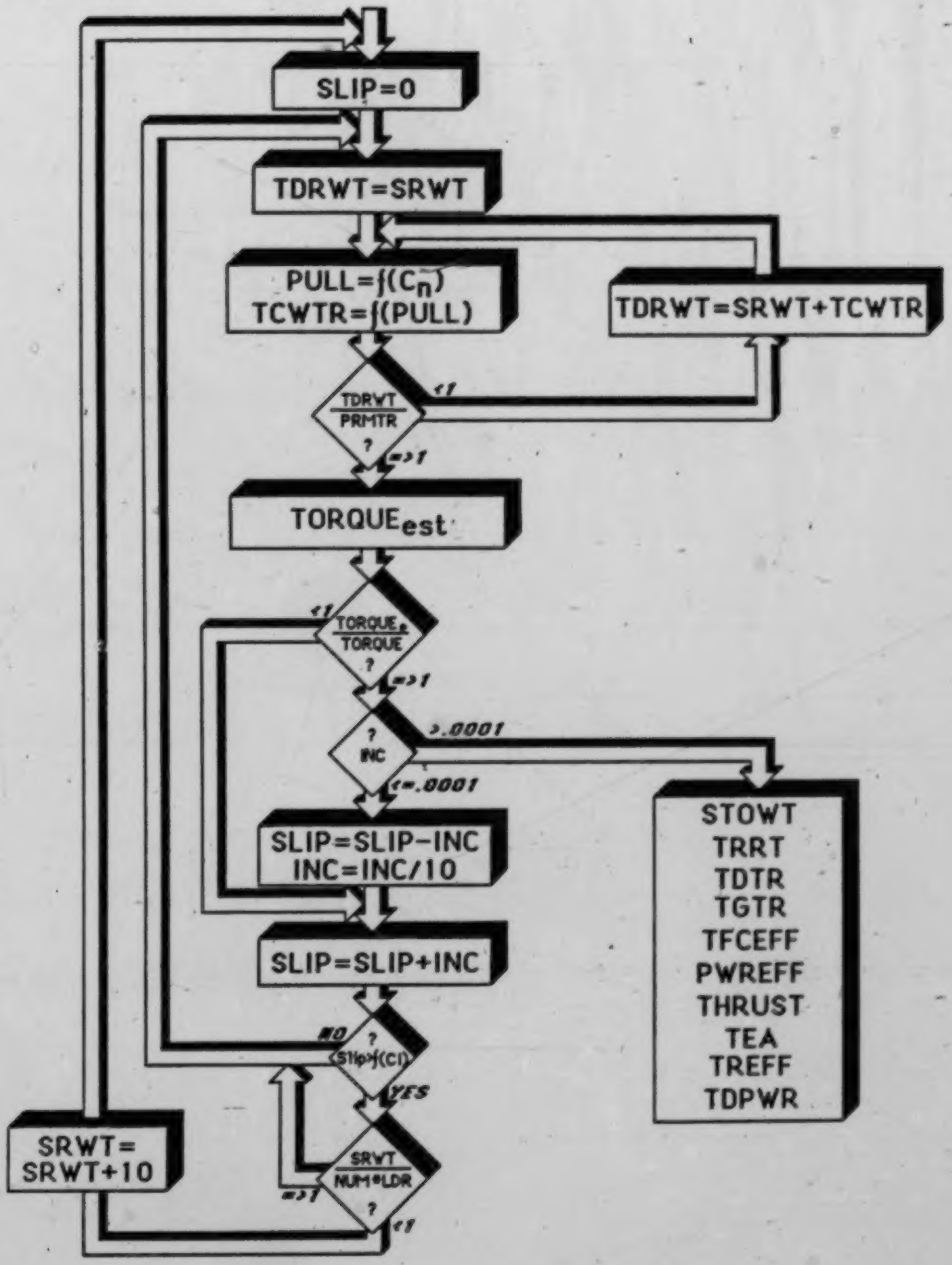

SLIP=0
TDRWT=SRWT
PULL=∫(C_n)
TCWTR=∫(PULL)
TDRWT=SRWT+TCWTR
TDRWT / PRMTR ?
<1
=>1
TORQUEest
TORQUEe / TORQUE ?
<1
=>1
? INC
>.0001
<=.0001
STOWT
TRRT
TDTR
TGTR
TFCEFF
PWREFF
THRUST
TEA
TREFF
TDPWR
SLIP=SLIP-INC
INC=INC/10
SLIP=SLIP+INC
? Slip>∫(CI)
NO
YES
SRWT / NUM*LDR ?
=>1
<1
SRWT=
SRWT+10

Figure 6.7. HELLAS model flow-chart.

### 6.7.2. Model algorithm

The central equation of the model was a variation of the Wismer and Luth (1974) equation,

$$P/W=0.75\ (1-e^{-0.3*C_n*S}) + (1.2/C_n+0.04) \qquad \ldots\ldots\ldots\ldots 6.40$$

where: P=Drawbar Pull

S=Slip

For the purposes of the model, equation 6.40 was multiplied by W to provide a value for Drawbar Pull. In addition the term $(1.2/C_n+0.04)*W$ was replaced by the total motion resistance. The algorithm of the model is the following:

1. The slip value was set to zero.
2. Calculation of the motion resistance.
3. Calculation of the Drawbar Pull using equation 6.40.
4. Calculation of the weight transfer using equation 6.2.
5. Calculation of the axle Torque.
6. Comparison of the calculated and known axle Torque.
7. If calculated Torque is less than known Torque then increment the slip or else go to 9.
8. If slip is greater than $\text{slip}_{\text{lim=f(Cone Index)}}$ then increment ballast and go to 1 or else go to 3.
9. Calculate the tractor performance parameters.

### 6.7.3. Discussion

The HELLAS is an all-tractor performance prediction model. The algorithm described above is straightforward and is based on mechanical relationships of the tractor.

The Wismer and Luth equation and the differences from the Zoz and Brixius version of the equation were discussed in a previous chapter. The only point that should be repeated is that the Wismer and Luth equation uses the Cone Index value in calculating the Tractive Quotient (Leviticus and Reyes, 1983a) whereas Zoz and Brixius (1979) use the rubber tire hardness.

Using the Cone Index value for in-soil tractor performance prediction, different conditions are established for each type of soil.

Model comparison is possible only with real data, since there is no similar complete model to compare with.

## 6.8. Comparison of the models

The models were compared in terms of the following four tractor performance parameters:

a. Travel Reduction (TR) or Slip
b. Drawbar Pull (DBPL)
c. Dynamic Traction or Pull Ratio (PR)
d. Tractive Efficiency (TE).

In addition, the models were compared implicitly in terms of ground speed and Drawbar Pull, through the Travel Reduction and Tractive Efficiency, respectively. For illustration purposes, the values obtained for a FORD TW-20 2WD tractor, a KUBOTA M5500 DT Front Wheel Assist (FWA) tractor and a CASE 4890 D 4WD tractor are presented in bar graphs for nine different soil-implement hitch combinations. The model comparison concerns all the possible combinations of firm, tilled and soft soil with integral, semi-mounted and towed implements. The tractor analysis data sheets are shown in Appendix C, Tables C.1, C.2 and C.3. The bargraphs for model comparison are shown in Figures C.1 to C.36 for the 2WD tractor, Figures C.37 to C.72 for the FWA tractor and Figures C.73 to C.108 for the 4WD tractor.

In terms of *Travel Reduction* the general trends are:

i. the TR decreases as the gear increases

ii. the TR decreases as the soil Cone Index increases.

Figures C.1-C.9, C.37-C.45 and C.73-C.81 present the TR comparison for the three models, for the 2WD, FWA and 4WD tractors, respectively. For the ASAE D230.4 model the TR is evenly distributed among soils, varying from 24% for firm soil/mounted implement to 38% for soft soil/towed implement for the 2WD tractor, from 27% for firm soil/mounted implement to 53% for soft soil/towed implement for the FWA tractor and from 17% for firm soil/mounted implement to 34% for soft soil/towed implement for the 4WD, at the lowest gear. The model shows insensitivity to the type of implement hitch except for soft soils. For the OECD model the TR is severely underpredicted, for all the soil-implement hitch combinations, varying from 4.4% for firm soil/mounted implement to 4.6% for soft soil/towed implement for the 2WD tractor, are 10.1% for all soil-implement hitchcombinations for the FWA tractor and from 6.8% for firm soil/mounted implement to 8.0% for soft soil/towed implement for the 4WD, at the lowest gear. For the HELLAS model the TR is widely distributed among soils, varying from 19% for firm soil/mounted implement to 42% for soft soil/towed implement for the 2WD tractor, from 19% for firm soil/mounted implement to 70% for soft soil/towed implement for the FWA tractor and from 18% for firm soil/mounted implement to 42% for soft soil/towed implement for the 4WD, at the lowest gear.

It should be mentioned that in soft soils (350 kPa) the slip increases uncontrollably due to the loading factor limitations under the current tire configuration. The ground speed shows the opposite trends compared to the TR.

In terms of the *Drawbar Pull* the trends are:

i. the DBPL decreases as the gear increases

ii. the DBPL increases as the soil Cone Index increases.

Figures C.10-C.18, C.46-C.54 and C.82-C.90 present the DBPL comparison for the three models, for the 2WD, FWA and 4WD tractors, respectively. For the ASAE D230.4 model the DBPL is widely distributed among soils, varying from 59 kN for firm soil/mounted implement to 38 kN for soft soil/

mounted implement for the 2WD tractor, from 26 kN for firm soil/mounted implement to 20 kN for soft soil/mounted implement for the FWA tractor and from 100 kN for firm soil/mounted implement to 56 kN for soft soil/towed implement for the 4WD, at the lowest gear. Because of the fact that the slip values for the FWA tractor in the soft soil exceeded the limits, the results can be considered as a typical example of erroneous results. The OECD model predicted lower DBPL for all the soil-implement hitch combinations, with little variation among soils and implement hitches for the FWA tractor. For the 2WD and 4WD tractor the model predicted lower values on firm soil and higher values on tilled and soft soil. The DBPL partially reflects the low slip values. The HELLAS model, compared to ASAE D230.4 predicted higher DBPL values at low gears and lower DBPL values at higher gears for the FWA tractor. For the 2WD and 4WD tractor the model predicted higher values at all the times. The DBPL varies from about 62 kN for firm soil/mounted implement to 54 kN for soft soil/towed implement for the 2WD tractor, from 27 kN for firm soil/mounted implement to 23 kN for soft soil/towed implement for the FWA tractor and from 120 kN for firm soil/mounted implement to 85 kN for soft soil/towed implement for the 4WD, at the lowest gear.

The *Pull Ratio* reflects the combined effect of slip, weight transfer and ballasting. The limitations applied to TR and DBPL are also applicable to PR. The general trends are:

i. the PR decreases as the gear increases

ii. the PR decreases as the soil Cone Index decreases.

Figures C.19-C.27, C.55-C.63 and C.91-C.99 present the PR comparison for the three models, for the 2WD, FWA and 4WD tractors, respectively. For the ASAE D230.4 model the type of implement hitch affects the PR differently for the three soils. The PR varies from 0.80 for firm soil/mounted implement to 0.32 for soft soil/mounted implement for the 2WD tractor, from 0.80 for firm soil/mounted implement to 0.45 for soft soil/mounted implement for the FWA tractor and from 0.79 for firm soil/towed implement to 0.34 for soft soil/towed implement for the 4WD, at the lowest gear. The PR in the soft soil has a different trend than the other soils, due to the excessive TR values. For the OECD model there is no significant change of the PR among the soils. The model also demonstrated immunity to the type of implement hitch. The OECD model uses different weight transfer coefficients from the implement to the tractor, compared to the HELLAS model. The HELLAS model shows better distribution of PR among soils compared to the other models, varying from 0.75 for firm soil/mounted implement to 0.44 for soft soil/towed implement for the 2WD tractor, from 0.66 for firm soil/mounted implement to 0.53 for soft soil/towed implement for the FWA tractor and from 0.65 for firm soil/mounted implement to 0.40 for soft soil/towed implement for the 4WD, at the lowest gear. The model showed immunity to the effect of the implement hitch.

The *Drawbar Power* is analyzed through the *Tractive Efficiency*, since they have the same trends. The TE is affected by the TR and DBPL. There is no general trend among the models.

Figures C.28-C.36, C.64-C.72 and C.100-C.108 present the TE comparison for the three models, for the 2WD, FWA and 4WD tractors, respectively. For the ASAE D230.4 model the validity of the TE value depends on the TR value, for when TR exceeds the 30% limit the results are not realistic. Figures C.70-C.72 show this fact clearly. In contrary Figures C.34-C.36 show a better response of the TE for a 2WD tractor, verifying the limitation of the model to 2WD tractors. The TE shows immunity to the effect of the implement hitch. The OECD model behaves differently than the other two models by not being able to reach a peak. The reason is the balancing of the available and the calculated Torque at very low TR values. The TE is directly proportional to the soil strength and shows immunity to the type of implement hitch. The HELLAS model behaves well for all the soils and implement hitch combinations, even when the TR exceeds the specified limits. The TE at both sides of the peak changes smoothly. The TE is directly proportional to the soil strength and shows immunity to the type of implement hitch. The peak of the curve varies from 84% for firm soil/mounted implement to 57% for soft soil/towed implement for the 2WD tractor, from 76% for firm soil/mounted implement to 49% for soft soil/towed implement for the FWA tractor and from 85% for firm soil/ mounted implement to 55% for soft soil/towed implement for the 4WD.

### 6.9. Discussion

A key factor during slip calculation and tractor performance optimization is ballast auto-incrementing. However, in various occasions, such as soft soils, the need for excessive ballast is beyond the load carrying capabilities of the tire. A solution to this problem can be the change of the tire configuration. The auto-incrementing of the tire configuration, such as duals, was considered and rejected, since the program would have gone too far in deciding on behalf of the user. The implemented auto-incrementing of the applied ballast on the tractor was considered the maximum that the program should do for tractor performance optimization.

Another factor that may be important in determining the soil-tractive device interaction is the *multi-passing effect* and the resultant changes in soil Cone Index. Specifically, the front tires of the tractor dynamically compact the soil and the rear tires move on a soil with higher Cone Index value. However, no information concerning the differences in terrain trafficability due to soil compaction was found in the relevant literature. For that reason the multi-passing effect was substituted with a motion resistance reduction on the rear traction devices to compensate for changes in soil strength during the farming operation. Coefficients of 0.95 for 2WD, 0.90 for FWA and 0.85 for 4WD tractors were used for this purpose. The coefficients were determined by the author based on the fact that, the soil compaction due to the combined effect of loading and shear stress application, is twice the compaction resulted from loading only.

### 6.10. Conclusions

The ASAE D230.4 model lacks flexibility due to the rigidity of the equations involved in the algorithm and the strict application of the limitations. The procedures involved for a mechanistic transfer of the nomogram into a computer simulation model are not very accurate.

The OECD model was designed for static tractor analysis and is not capable of handling the effects of weight transfer in tractor mechanics. The results of this model can not be directly evaluated. The modifications of the model with the introduction of the dynamic weight and the tire effective arm directly affected the results of the model. The slip values, calculated by this model, are unrealistic and imply that the empirical equations may need revision.

The HELLAS model was found the most flexible under any conditions, with smoother transitions, less discrepancy and more realistic response to soil strength. The model was assembled from compatible, broadly accepted tractor performance relationships, the validation of which can be located in the relevant literature. Even though in-soil experimentation is required for validation of the model, the HELLAS model seems to be the most suitable for further applications.

# 7. DATABASE MANAGEMENT SYSTEM FOR TRACTOR ANALYSIS

## 7.1. Software development

The integrated software package which is presented in this chapter, is a complete tree-structured hierarchical DBMS. Eight functions and a help facility were implemented for software friendliness and functionality. The core of the software is the three in-soil tractor performance prediction models, which were described in the previous chapter. The idea for an integrated software package emerged during program development.

The program was developed in several stages between January 1984 and December 1985. The criteria for distinguishing the stages of program development were the programming language, the hardware that was involved, the degree of software integration, the user friendliness and the implementation of the DBMS. The successive stages of software development were called *versions*.

The *first version* of the software was based on the Waterloo MicroFortran V1.2 programming language for the IBM PC, operated through the Waterloo Editor V1.2. The tasks performed by this version were data retrieval, data processing and output of the results to the printer. Editor inefficiency, program length, interpreter inefficiency in error trapping and limited I/O capabilities were the major drawbacks. Disk access during program execution was limited. A relational DBMS was used slowing program execution. The tractor analysis was reliable. The tire information was collected from Handbooks supplied by various tire companies (GOODYEAR, BFGoodrich, Firestone, etc.) and the 1984 SAE Handbook Vol.4. The tire information was in a single data file and english units were used.

The *second version* of the software was characterized by reprogramming the MicroFortran program in Microsoft BASICA V2.00. Structured programming was introduced and the tasks were selected through a main menu. Stand-alone input-output tractor data files replaced the batch tractor file. The DBMS changed from relational to hierarchical. The tractor data files were coded according to their NTTR number. The output file was created by merging the input and the derived information. MicroFortran utility programs were used for database management.

In the *third version* of the software the statistical package and the graphics package were added. New features for user friendliness, program efficiency and reliability were included. The addition of the new routines caused the entire structure of the program to be altered, introducing subroutines of common functionality. Menus and I/O operations were defined as general purpose subroutines. Memory efficiency and software integration were improved increasing program complexity. Major problems were program modification and elimination of subroutine interaction. Both tractor and tire source files were expanded. New information was added in the tractor files. The tire files were updated using information from the ASAE Standards (1984) and The Tire and Rim Association, Inc. Yearbook (1984).

The *fourth version* of the software included the in-soil tractor performance prediction models. The utility programs for database management were improved and linked to the main program using a CHAIN (BASIC, 1982) technique. Additional general purpose subroutines were created. Two major changes in the DBMS were the change of the tractor files from sequential to random access, and the introduction of a new file classification system allowing easier database management. The DBMS is shown in Figures 7.1 and 7.2 for Ordinary and Simulation structures, respectively. The tire records were classified into different random access files named after the manufacturing company. One significant improvement was the introduction of directories. The tractor database directory was a sequential file including the make of tractor and the file name. The tire database directory was a sequential file based on tire sizes and ply ratings. Three tire file directories were available for search.

The *fifth version* of software featured the expansion of the program for use in an IBM PC with either Monochrome or Color/Graphics Adapter. The utility programs were improved facilitating tractor and tire database management, and disk management from within the program. The tire directory files were changed to random access files. The

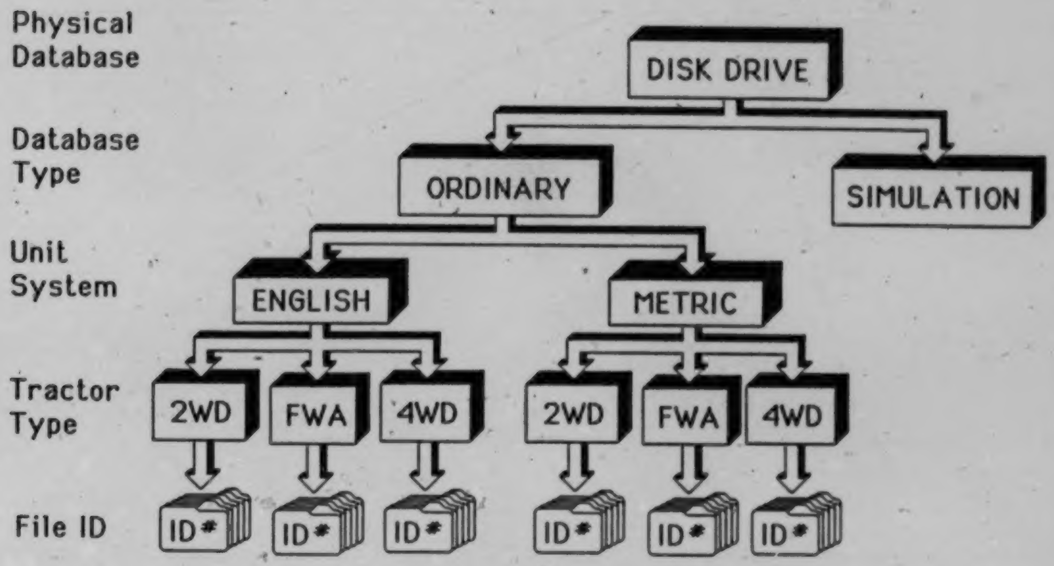

Physical Database
DISK DRIVE
Database Type
ORDINARY
SIMULATION
Unit System
ENGLISH
METRIC
Tractor Type
2WD
FWA
4WD
2WD
FWA
4WD
File ID
ID*
ID*
ID*
ID*
ID*
ID*

Figure 7.1. DBMS - Ordinary database structure

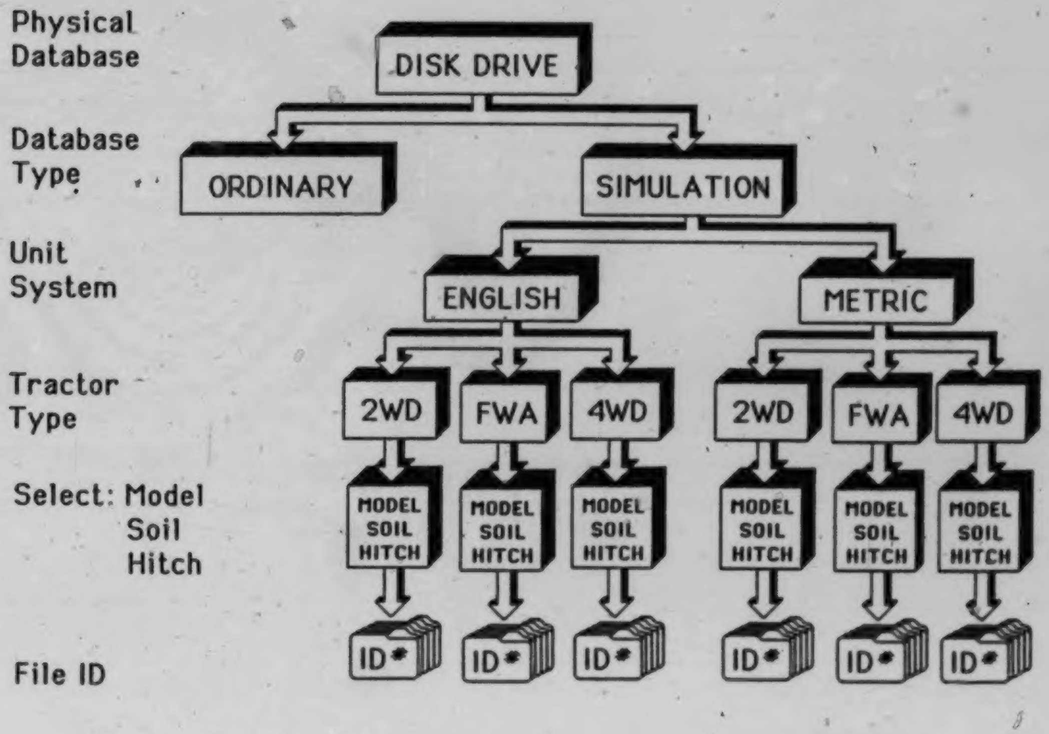

Physical Database
DISK DRIVE
Database Type
ORDINARY
SIMULATION
Unit System
ENGLISH
METRIC
Tractor Type
2WD
FWA
4WD
2WD
FWA
4WD
Select: Model Soil Hitch
MODEL SOIL HITCH
MODEL SOIL HITCH
MODEL SOIL HITCH
MODEL SOIL HITCH
MODEL SOIL HITCH
MODEL SOIL HITCH
File ID
ID*
ID*
ID*
ID*
ID*
ID*

Figure 7.2. DBMS - Simulation database structure.

integrated software was configured in two diskettes. The first diskette contained the system files and the source libraries. The second diskette contained application and data files, included nine BASICA programs, one document file and six tire data files.

The *sixth version* of the program was the stage during which the various BASIC programs were assembled in one program and Compiled. The integrated software became a single-disk single-program application, including the DOS Assembly language subroutines, the tire libraries and the help facility. Figure 7.3 shows the structural tree of the program.

## 7.2. Software attributes

From the programming point of view the most important attributes of the integrated software were software structure, efficiency, integration, multitasking, user friendliness, modifiability, expandability, uniformity, reliability and database capabilities.

In terms of structure, the program was modular with a central routine linking the nine available options in a tree-structure. The tree-structure of the program uses a set of common functionality subroutines.

Memory efficiency through multiple use of variables and arrays, time efficiency through the development of more sophisticated algorithms, and structure efficiency through

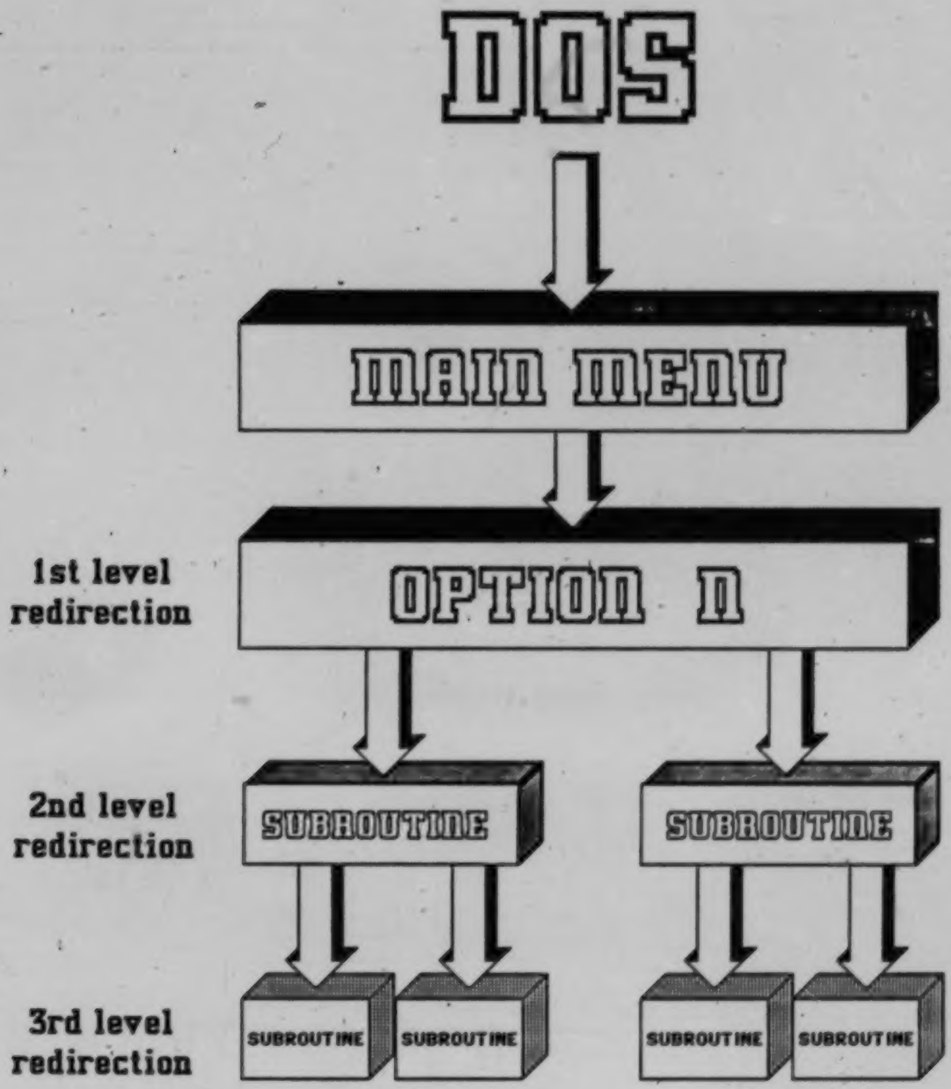

DOS
MAIN MENU
1st level redirection
OPTION N
2nd level redirection
SUBROUTINE
SUBROUTINE
3rd level redirection
SUBROUTINE
SUBROUTINE
SUBROUTINE
SUBROUTINE

Figure 7.3. Structural tree of the program

the use of many small general purpose subroutines, resulted in higher software modifiability and performance, and increased integration. The software integration was measured in terms of information sharing among the various options of the software. In terms of multitasking, the eight executable routines and the on-line HELP cover a wide range of functions.

User friendly programming was attempted for user comfort through the use of explicit menus and messages and an on-line HELP. It is up to the user to evalute the effort.

Software expansion is possible through user programming in Assembly language. User access to the libraries is allowed. The user accessible tire files was named USER.

Software uniformity is defined in terms of I/O handling procedures and sharing of information. Software uniformity was a need for program compilation. The database capabilities of the software increased with the introduction of facilities for creating new records, editing and displaying existing records, and updating and searching the database. Use of random access files and directories significantly improved the efficiency of the hierarchical DBMS.

Software reliability was dependent on the computer numerical accuracy and the structure of the tractor performance prediction algorithms.

## 7.3. Limitations

The software limitation of the package is that only one file can be active at a time.

The hardware limitation is the numerical accuracy of the IBM PC, due to the design of the microprocessor. The hardware limitation was revealed during statistical analysis, where calculations of high accuracy were required.

## 7.4. Software structure and implementation

All the routines involve subroutine calls in various depths. After completion of a task the control may or may not return to the Main Menu, since branching from one routine directly to another was implemented. Thirty seven program subroutines were written to perform number and string manipulation, I/O operations (screen, printer and disk drives), mathematical calculations, logical relations, and random access file handling. The subroutine map, providing addresses, titles and comments, is given in Appendix B, Table B.4. Figure 7.4 represents the block diagram of the software. The flow-chart of each routine will be presented along with the description of each routine.

The program levels were identified by labels displayed at the top of the screen. The menus were either a list of options or preformated pages. The bottom of the screen was reserved for messages and user inputs.

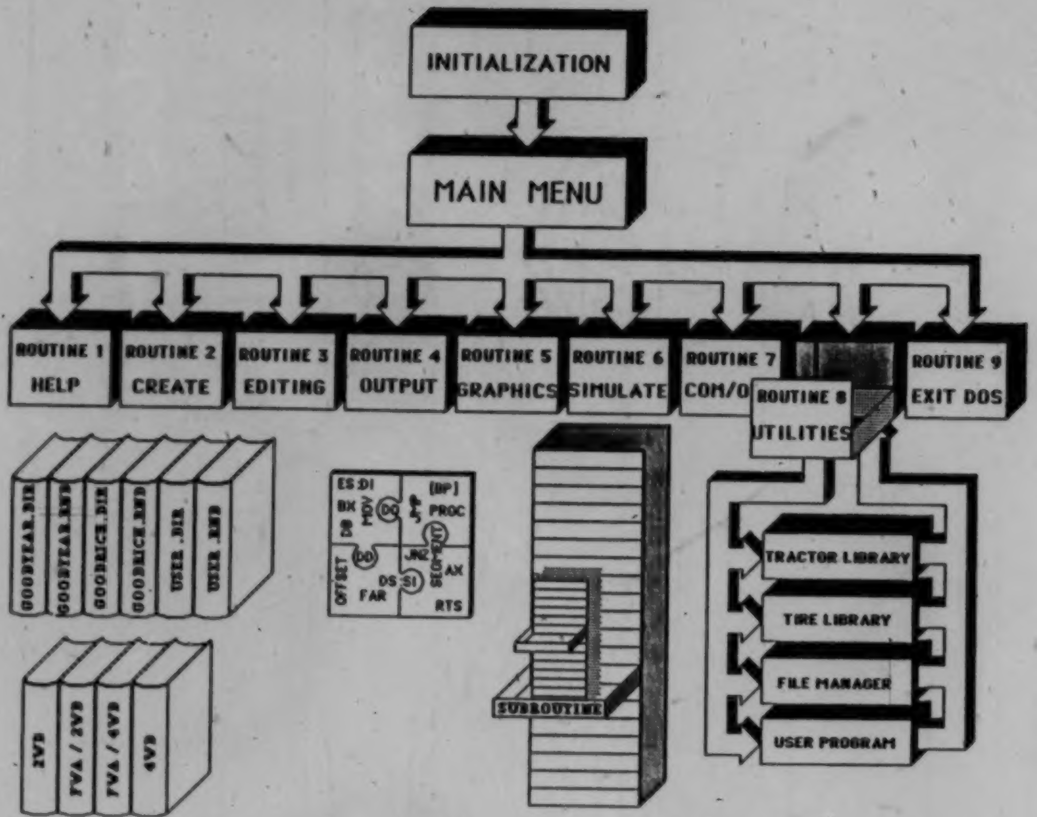

INITIALIZATION
MAIN MENU
ROUTINE 1 HELP
ROUTINE 2 CREATE
ROUTINE 3 EDITING
ROUTINE 4 OUTPUT
ROUTINE 5 GRAPHICS
ROUTINE 6 SIMULATE
ROUTINE 7 COM/O
ROUTINE 8 UTILITIES
ROUTINE 9 EXIT DOS
GOODYEAR.DIR
GOODYEAR.RWD
GOODRICH.DIR
GOODRICH.RWD
USER.DIR
USER.RWD
2WD
FWA / 2WD
FWA / 4WD
4WD
ES:DI
BX
DB
MOV
DO
JMP
[BP]
PROC
SEGMENT
DD
OFFSET
JNZ
AX
DS:SI
FAR
RTS
SUBROUTINE
TRACTOR LIBRARY
TIRE LIBRARY
FILE MANAGER
USER PROGRAM

Figure 7.4. Block diagram of the software

The function keys F1, F2, F3, F4, F5, F6 and F10, located at the left side of the keyboard, were assigned special tasks. The ESC key was used to interrupt an activity. The editing keys of the numerical keypad, located at the right side of the keyboard, were also assigned various functions. The tasks assigned to all these keys are described in Appendix B, Table B.5.

The tree-structure of the software, comprises three levels of menus:

Level 1. Main Menu

Level 2. No-File Menu

Level 3. Routine dependent menus.

The Main Menu provided nine options. The No-File Menu requested for the physical location of the database (drive A or B) to initialize a database. Entering a routine, special menus guided the user for parameter selection.

Following the tree-structure from top to bottom, the three levels were used sequentially. However, the program execution can return to any level using alternate paths. ESC (soft interrupt) and function key F10 (hard interrupt) are provided for this purpose.

The database classification system and information recognition depend on the input parameter format. The field that contains the NTTR number represents the ID of the tractor file. Any alphanumeric user entry is acceptable in this field. Numbers less than one thousand or greater than three thousand are recommended as user entries. The requested tire information is database dependent. The database for 2WD and FWA tractors requests front and rear tire information, whereas the database for 4WD tractors requests inner and outer tire information. The tire size assignment rules are given in Appendix B and must be followed at all times, since this is the only way for the database to identify and locate the appropriate tire information. Upper case letters are significant for tire size recognition. The various field entries are interpreted according to an internal format.

### 7.5. Program options

The program options were selected through a Main Menu. The Main Menu was the first level of the program providing primary control of the following functions:

1. Display H E L P facility
2. Create a new tractor file
3. Edit an old tractor file
4. Retrieve a database file
5. Run Graphics package
6. Run Simulation package
7. IBM Serial Communications
8. Run Utilities package
9. Terminate program execution

The functions are examined in detail in the following sections.

### 7.5.1. Display HELP facility

The HELP facility is an on-line textfile, providing program general information.

The three stages of the HELP facility evolution were a sequential file, a random access file and a program built-in Assembly language subroutine.

The HELP facility is invoked either through the Main Menu or through the function key F1.

### 7.5.2. Create a new tractor file

The second option of the integrated software facilitated the creation and processing of a new database record. The flow chart of the routine is shown in the Figure 7.5.

In order to establish a new record, the information was entered in two preformated pages. The first page, involving twenty one parameters (listed in Appendix B, Table B.3) requested tractor design information using a format with field entries. A special editor was designed to handle the field entries, which were treated as strings of characters assembled one character at a time. Special functions were assigned to the editing keys. The second page requested information for six tractor performance parameters sorted in a gear ascending order. The requested tractor performance parameters were described in section 6.2. The number of

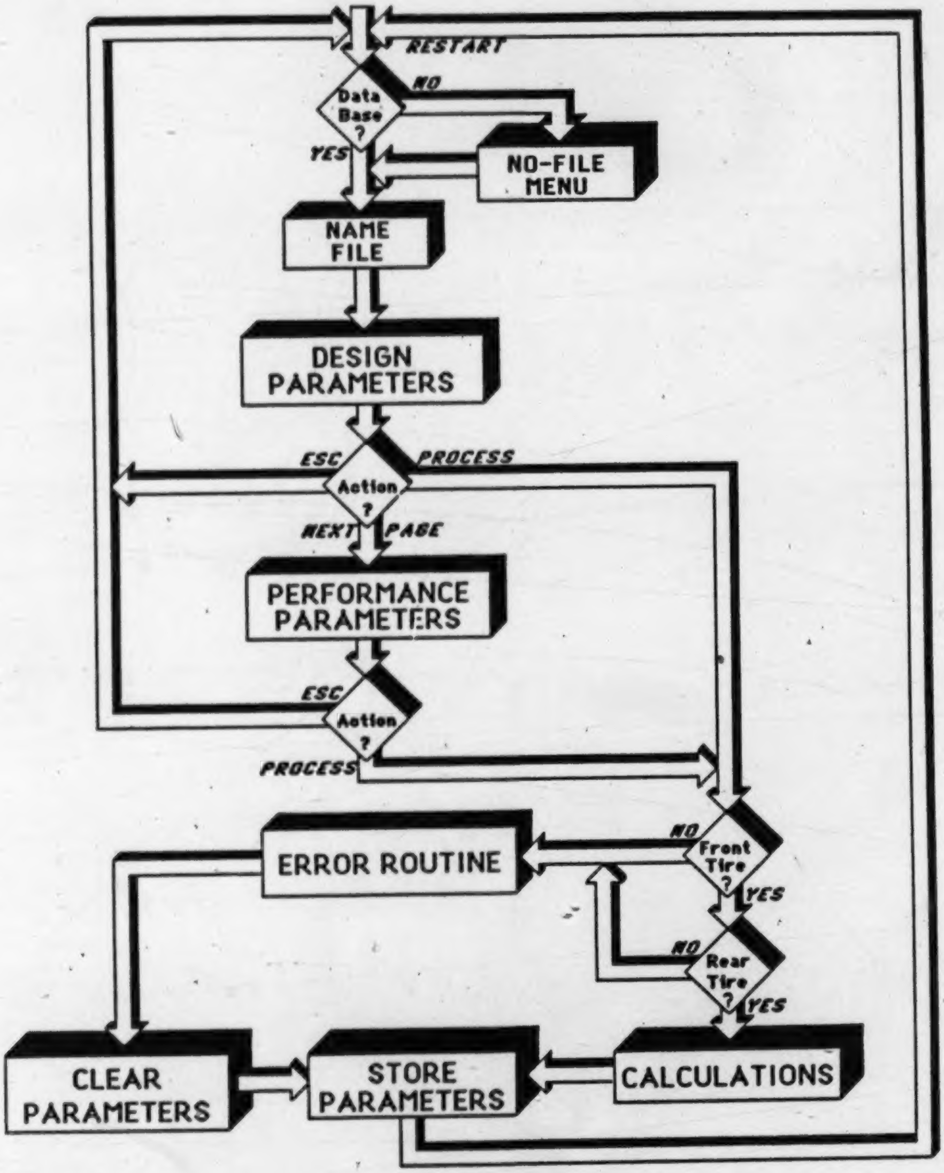

RESTART
Data Base ?
NO
YES
NO-FILE MENU
NAME FILE
DESIGN PARAMETERS
ESC
PROCESS
Action ?
NEXT PAGE
PERFORMANCE PARAMETERS
ESC
Action ?
PROCESS
ERROR ROUTINE
NO
Front Tire ?
YES
NO
Rear Tire ?
YES
CLEAR PARAMETERS
STORE PARAMETERS
CALCULATIONS

Figure 7.5. Flow-chart of create routine

observations, which was specified in page one, determined the number of entries per parameter. A maximum of twenty entries per parameter was possible. The page was filled in a unidirectional way and no means for altering an entry were provided. Table B.8 in Appendix B, shows the layout of the random access tractor file with the location of the parameters and the type of fields.

For file processing tire information was retrieved from the appropriate database. The data processing involved the computations described in section 6.3. If no tire information was found the derived parameters were passed to the disk with a zero argument. Tractor database directory updating was performed.

### 7.5.3. Edit an old tractor file

The database editing routine performed the modification and processing of existing database files. Figure 7.6 illustrates the flow-chart of the editing routine. The edited files must have been created either using the previous routine or the appropriate utility, due to the special format requirements of the random access files.

The tractor design and performance parameter menus, described in the previous routine, displayed the input tractor information. The user could modify the entries, change page, proceed to data processing or terminate the editing.

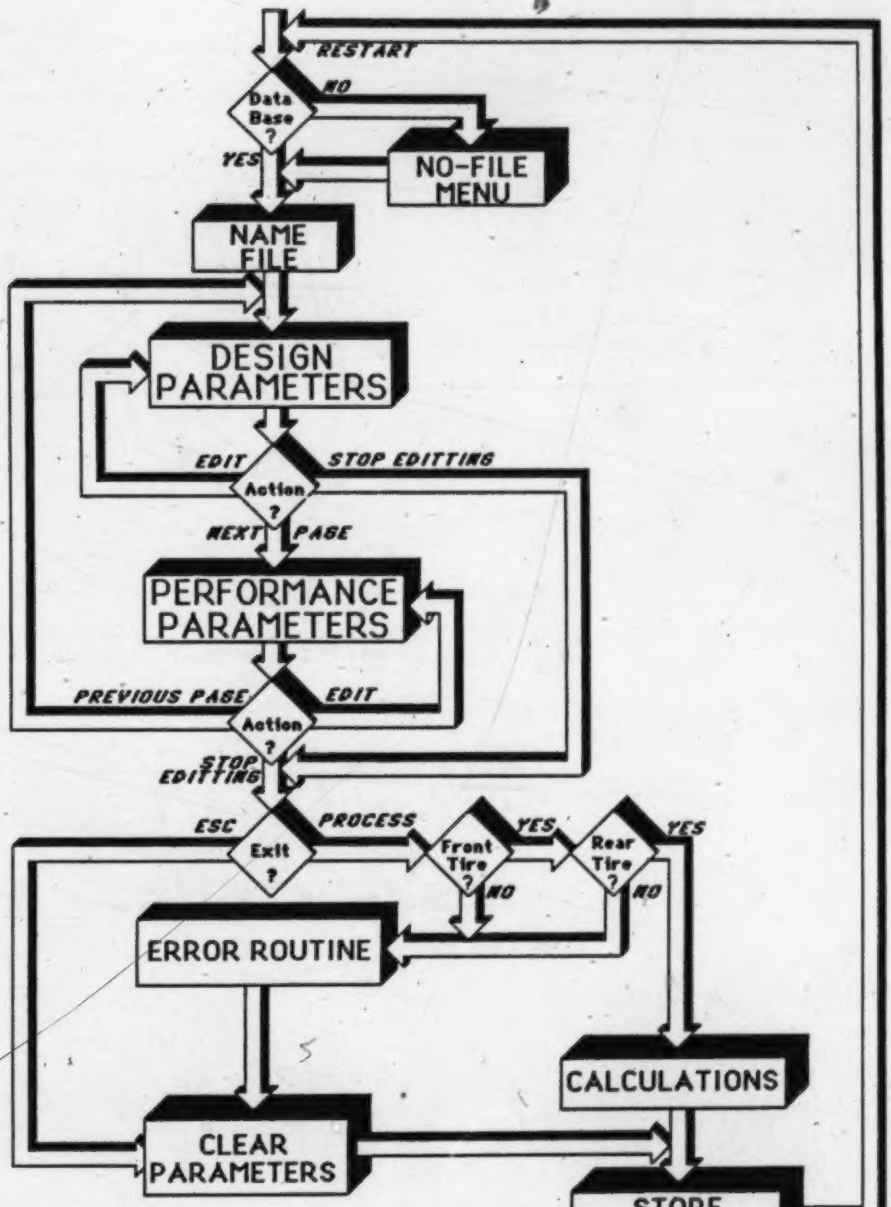

RESTART
Data Base ?
NO
YES
NO-FILE MENU
NAME FILE
DESIGN PARAMETERS
EDIT
STOP EDITTING
Action ?
NEXT PAGE
PERFORMANCE PARAMETERS
PREVIOUS PAGE
EDIT
Action ?
STOP EDITTING
ESC
PROCESS
Exit ?
Front Tire ?
YES
NO
Rear Tire ?
YES
NO
ERROR ROUTINE
CALCULATIONS
CLEAR PARAMETERS
STORE PARAMETERS

Figure 7.6. Flow-chart of edit routine

The modification of the first page was performed using the special editor that was mentioned in the previous routine. The modification of the second page was carried out using the general purpose editor. The editing keys were assigned special function. The modified variables were field adjusted and highlighted. The file processing followed the same procedure as the previous routine.

### 7.5.4. Retrieve a database file

This routine directed the tractor information to the standard output devices. The two available options were S for output to the screen and P for output to the printer. If the device was not supported, an error message was displayed. Figure 7.7 illustrates the flow-chart of this routine.

On the screen the file was displayed in four pages. Analytically, the information displayed on every page is given in Appendix B, Table B.8. The control over the four pages was implemented on the editing keys facilitating bidirectional window refresh.

The output to the printer provided tractor information in a tabular format. Page formatting was implemented. The user was required to adjust the perforation of the paper to the head of the printer.

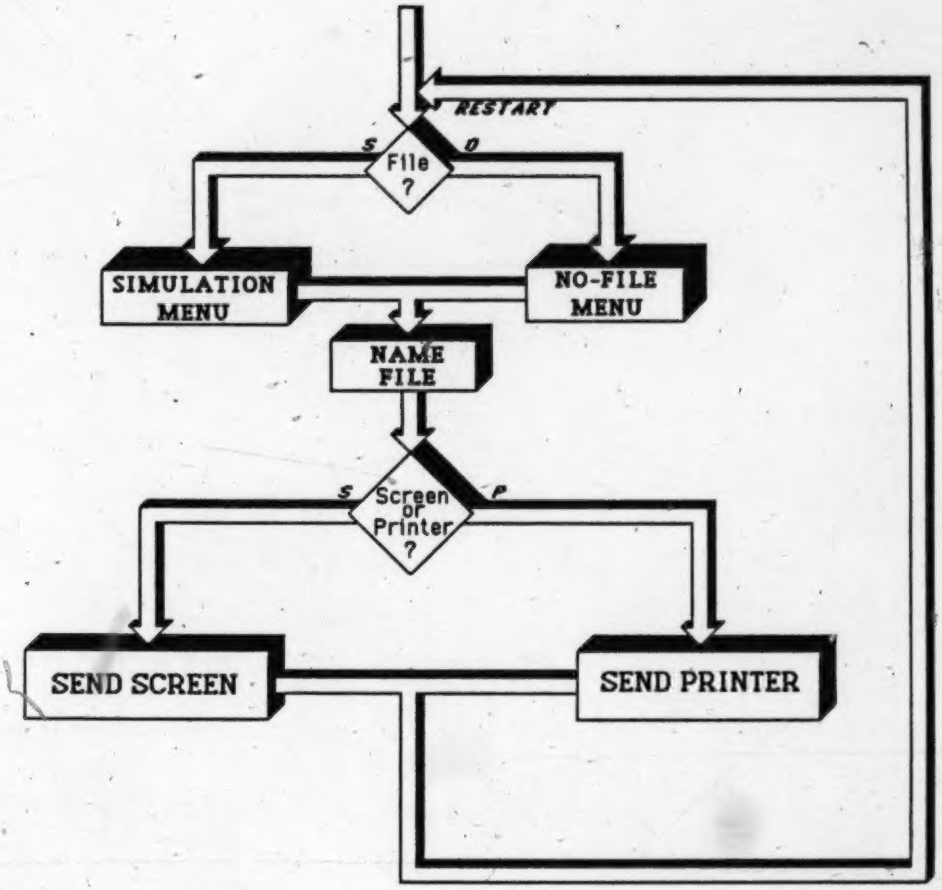

RESTART
S
D
File ?
SIMULATION MENU
NO-FILE MENU
NAME FILE
S
P
Screen or Printer ?
SEND SCREEN
SEND PRINTER

Figure 7.7. Flow-chart of retrieve routine

### 7.5.5. Run Graphics package

The graphics package presented a curve on the screen describing the relationship between two tractor performance parameters. The equation describing the curve was determined by the regression analysis algorithm, presented in the previous chapter. Figure 7.8 illustrates the flow-chart of the Graphics package.

If a Color/Graphics Display Adapter card is available, the curve is continuous and is obtained using graphics instructions at the high resolution mode. If a Monochrome/ Printer Display Adapter is available the curve is discrete and is obtained using asterisks, in an attempt to emulate the graphics process. By pressing the Shift-PrtScr keys the contents of the screen can be printed on the matrix printer.

All of the twenty two parameters of the menu could be combined using the editing keys.

Before running the graphics package, several flags were tested in order to avoid erroneous results. If any one of the flags was raised, data processing was halted and an error message was displayed at the bottom of the screen. One point of inadequacy of the Graphics package, as well as the entire software, is the inability to combine information from different data files on the screen, prohibiting direct visual comparison of information.

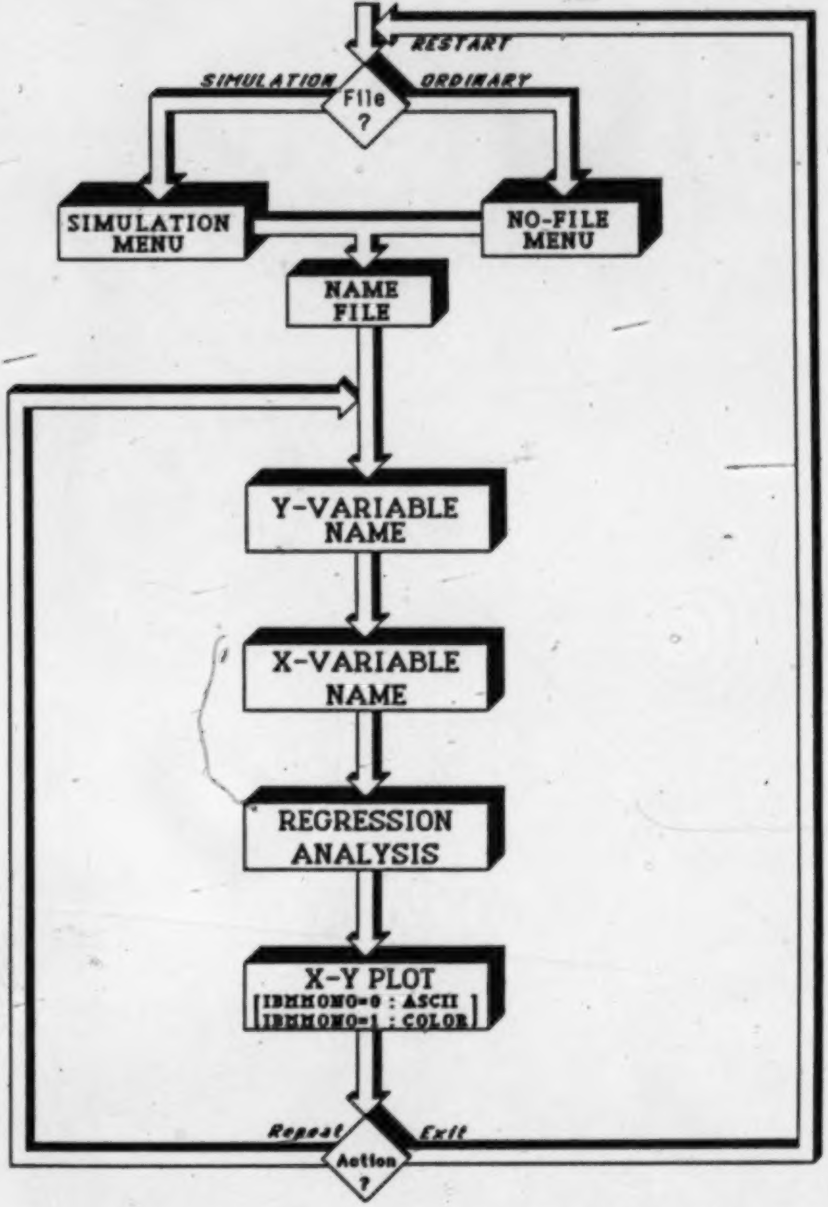

RESTART
SIMULATION
ORDINARY
File ?
SIMULATION MENU
NO-FILE MENU
NAME FILE
Y-VARIABLE NAME
X-VARIABLE NAME
REGRESSION ANALYSIS
X-Y PLOT
[IBMMONO=0 : ASCII]
[IBMMONO=1 : COLOR]
Repeat
Exit
Action ?

Figure 7.8. Flow-chart of the Graphics package

### 7.5.6. Regression analysis algorithm

The regression analysis was performed over 484 different pairs of data sets, which were selected through a menu offering two listings of twenty two parameters that can be combined. A best fit curve is determined by the least squares method to establish an equation describing the pair of data sets. Using the best fit equation sixty data points were calculated. The best fit equation was selected from one of the following nine equations, using the *coefficient of determination* $r^2$:

[1] $Y = A + B * X$ .................................7.1

[2] $Y = A * EXP(B * X)$ ............................7.2

[3] $Y = 1 / (A + B * X)$ ...........................7.3

[4] $Y = A + B / X$ .................................7.4

[5] $Y = A + B * LOG(X)$ ............................7.5

[6] $Y = A * X^B$ ...................................7.6

[7] $Y = X / (A + B * X)$ ...........................7.7

[8] $Y = A + B * X + C * X^2$ .......................7.8

[9] $Y = A + B * X + C * X^2 + D * X^3$ ..............7.9

Equation 7.1 is linear. Equations 7.2 to 7.7 are not directly linear but they can easily be transformed into linear equations and processed using linear regression analysis, like equation 7.1. At the end of the calculations on the transformed set of equations, the results should be adjusted applying inverse transformation. The equations involved in the algorithm for the linear regression are the following:

a. Sum of X

$SX=SX+X_i\ (i=1,\dots,n)$ ........................................7.10

b. Sum of $X^2$

$SX2=SX2+(X_i)^2$ ........................................7.12

c. Sum of Y

$SY=SY+Y_i$ ........................................7.13

d. Sum of $Y^2$

$SY2=SY2+(Y_i)^2$ ........................................7.14

e. Sum of cross products XY

$SXY=SXY+(X_i*Y_i)$ ........................................7.15

f. Slope of the regression line

$SLP_j=(NOBS*SXY-SX*SY)/(NOBS*SX2-SX^2)$ ....................7.16

g. Intercept (b)

$RX_j=(SY-SLP_i*SX)/NOBS$ ........................................7.17

h. Coefficient of correlation

$RCC=(SXY-SX*SY/NOBS)/\sqrt{((SX2-SX^2/NOBS)*(SY2-SY^2/NOBS))}$ ...7.18

i. Coefficient of determination

$R2_j=RCC^2$ ........................................7.19

k. Error sum of squares

$SSE=SY2-(SY^2/NOBS)-SLP_j*(SXY-SX*SY/NOBS)$ ................7.20

l. Standard error of estimate

$SE_j=\sqrt{(SSE/(NOBS-2))}$ ........................................7.21

When a subscript (i) is associated with a variable an array is implied. When a subscript (j) is associated with a variable a statistical parameter is implied. The theoretical validation of the above set of equations is described explicitly by Steel and Torrie (1980), chapter ten, titled Linear Regression.

Equations 7.8 and 7.9 represent a second and a third degree polynomial respectively and the best fit equation is calculated using Multiple Linear Regression analysis. The equations involved in multiple linear regression using matrix notation, are the following:

a. Coefficients of best fit equation

$X'X * b = X'Y$ ........................................7.22

b. Coefficient of multiple correlation

$R2=(SSR-SY^2/NOBS)/(SY2-SY^2/NOBS)$ ........................7.23

where: SSR = Sum of Squares (model); (b +.x X'Y).

c. Standard error of estimate

$SE=\sqrt{((SY2-SSR)/(NOBS-3))}$ ..............................7.24

A matrix with a prime is the original matrix transposed. Chapters twelve to fourteen of Steel and Torrie (1980), give the theoretical background of the Multiple Linear Regression.

Equation 6.22 involves matrix division between matrices X'X and X'Y to determine the best fit equation coefficients. Direct division of the matrices X'X and X'Y could not be implemented, therefore the matrix X'X was inverted and the inner product of the inverse matrix $(X'X)^{-1}$ with the matrix X'Y was calculated. An algorithm developed by Wolfe and Koelling (1983), attempting matrix inversion by making the matrix first upper and then lower triangular. The algorithm was tested independently from the main program to eliminate any kind of interference, but did not give the expected results compared to an APL program that was used as standard. Under these circumstances the algorithm was rejected.

The solution for matrix inversion was found in Steel and Torrie (1980), pg. 295, by a generalized equation. The computations were very complicated and extreme caution was required in the use of the matrices. The insufficient number of significant digits of the double precision numbers implemented on the IBM PC, had the tendency to multiply small errors through the iterative computations. The approach for the calculation of the best fit equation can not be characterized as "orthodox"; however, it is effective.

Discussing the results of the statistical analysis, the following can be stated:

a. the values of the *coefficients of the equations* calculated in the IBM PC were identical to the coefficients calculated by the SIMPREG, at least to the fourth decimal digit;

b. the values of the *coefficients of determination* calculated in IBM PC were identical to the values calculated by the SIMPREG, to the third decimal digit;

c. the values of the *standard deviation of estimate* calculated in IBM PC were identical to the values calculated by the SIMPREG, to the third decimal digit;

d. the best fit equation was selected by the program, based on the values of the coefficients of determination; the selection of the best fit equation was proven reliable.

Usually, the statistical analysis for defining the best fit equation is performed in APL, which is extremely powerful for this purpose. One of the utility programs available at the Agricultural Engineering Department of the University of Alberta, implemented in the main computer (Amdhal 6), is the ANBA:SIMPREG, which performs regression analysis and is highly reliable. The IBM PC implemented regression analysis algorithm was compared to the MTS implemented SIMPREG using as criterion the accuracy of the results. The limited accuracy of the IBM PC implemented regression analysis should be attributed to the hardware limitations of the microcomputer.

Beside the MTS implemented APL, a Waterloo MicroAPL V2.00 is available for the IBM PC, but it is not capable of handling high accuracy calculations such as matrix inversion. In addition, use of different languages was not desirable due to the loss in software integration and uniformity, loss in user comfort and difficulty in matching file structures. Therefore, the implementation of the statistical analysis in BASIC was essential.

### 7.5.7. Run Simulation package

The simulation package included three in-soil tractor performance prediction models, which were examined in detail in the previous chapter.

A menu provided the selection of tractor performance model, type of soil and type of implement hitch. By selecting the type of soil a default Cone Index value was assumed. The user was given the option to override the Cone Index value. The flow-chart of the Simulation package is shown in Figure 7.9.

The option of saving the simulation file was provided. The output file name was assembled by the program using the file ID, the soil type, the type of implement hitch and the model. The code for reading the output filename is as follows:

a. soil: S1=firm; S2=tilled; S3=soft;

b. implement: I1=mounted; I2=semi-mounted; I3=towed;

c. model: ML1=ASAE 230.4; ML2=OECD; ML3=HELLAS.

The file name reads as [*ID*][*S#*][*I#*].[*ML#*].

### 7.5.8. Serial Communications

The serial communications of the IBM PC with a remote computer required the presence of a Serial Communications Adapter (RS-232C). The program to support serial communications for the time being has not been implemented.

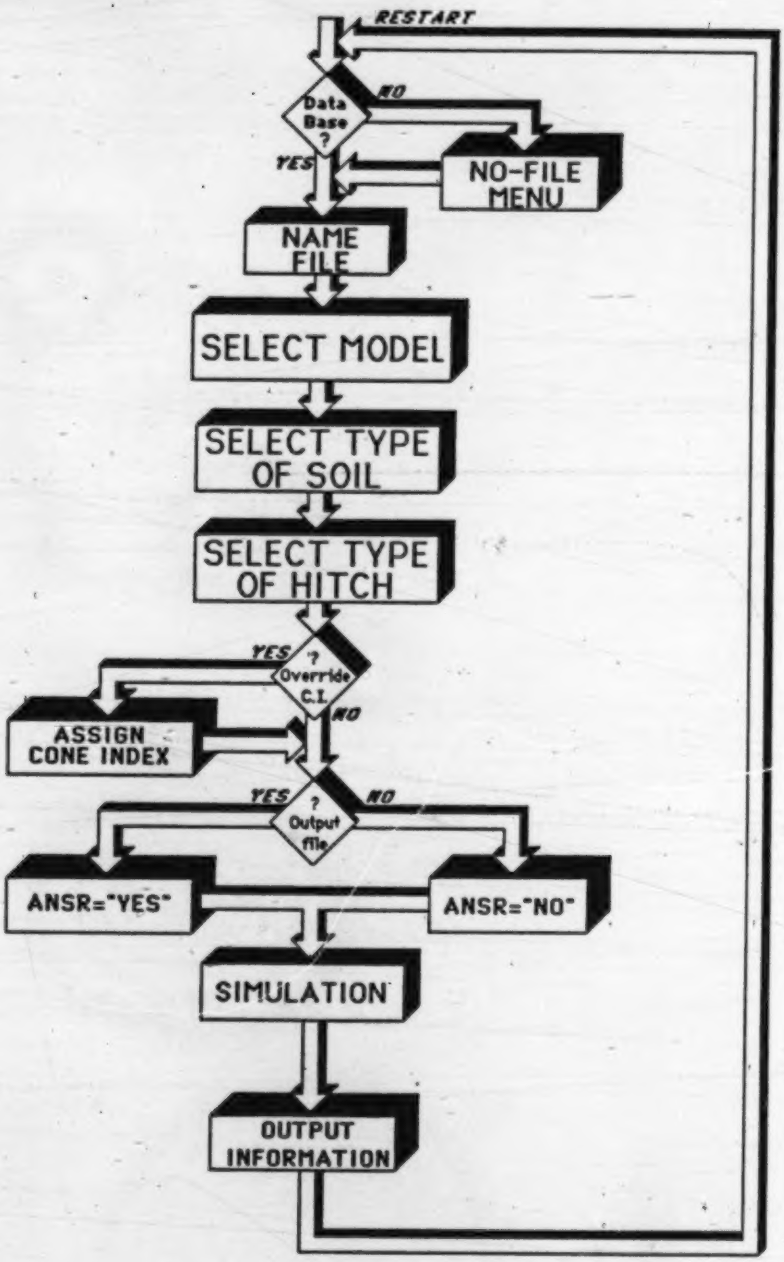

RESTART
Data Base ?
NO
YES
NO-FILE MENU
NAME FILE
SELECT MODEL
SELECT TYPE OF SOIL
SELECT TYPE OF HITCH
YES
? Override C.I.
NO
ASSIGN CONE INDEX
YES
NO
? Output file
ANSR="YES"
ANSR="NO"
SIMULATION
OUTPUT INFORMATION

Figure 7.9. Flow-chart of the Simulation package.

### 7.5.9. Utility programs

Four utility programs were available as extension to the main program. Protection of the database against misuse and correcting actions, were implemented. The four available utilities were:

a. Tractor library utility
b. Tire library utility
c. File management utility
d. USER defined program

Pressing of ESC issued an interrupt request, which was acknowledged and processed at the end of each cycle, minimizing the chances of losing files due to uncontrolled interrupts. Misuse of the I/O facilities caused the display of appropriate error messages.

#### 7.5.9.1. Tractor library utility

The tractor library utility converted tractor records, read from a sequential source file, into individual random access object files compatible with the DBMS. An internal format was used during read/write operations.

Batch file processing or processing of selected records of the source file was possible. Batch file processing was the default state, starting from the first record of the source file and stopping after processing one hundred records or when an End Of File was encountered, whichever occurred first. The processing of a set of records required the number of the records to be processed and the ordinal number of the starting record. The user was provided with a "search" tool to locate a record in the source file, using the file ID. Once the record was located its ordinal number was automatically assigned as the starting record.

The utility involved one source and two object files. The source file could be any valid DOS file name. Default drive was assumed to be A and default extension was assumed to be SIU. The object files had no real default values. The filenames were assembled by the information obtained during the several steps of the utility using four segments:

[*drive*]:[*ID*][*unit system*].[*tractor type*]

Two types of object files were generated in the destination drive. Object files in English units were created using a unit conversion algorithm. The object file unit system formed the second half of the object file name. The tractor type was requested in order to form the extension of the object file. Tractor type and unit system designated a distinct database class and subclass, respectively.

The first half of the random access tractor data file name represented the file ID (NTTR number or equivalent). The first half of the directory file name was ORD and this file was created automatically with the same drive, unit system and extension specifications as the individual object tractor files. When opening a database a search was performed for a directory file.

Due to the limitations in the source file format, the files FWA2WD.SIU, FWA4WD.SIU and 4WD.SIU were recommended for use. These files were source libraries and were available for editing. The user could insert new records using a word processor with the only limitation of format compatibility. It is highly recommended to insert the new records in the appropriate existing source files instead of creating new ones.

Interrupting the process by pressing ESC caused all open files to be closed to avoid loss of files. Two limitations were that the source file should be an ASCII[4] file and that the source file format should be compatible with the program's internal pattern.

#### 7.5.9.2. Tire library utility

The tire library utility facilitated sequential to random access tire file conversion, tire file inspection, and updating of the USER tire files.

During format conversion two random access object files were created. Only the source filename and the destination drive were requested. The default drive for all three files was A. The default for object and directory filenames, was the source filename. The default extension for the source tire-file was DAT, for the object tire file was RND and for the directory file was DIR. One of the source libraries GOODYEAR.DAT, GOODRICH.DAT and USER.DAT should be used as a source file, since the main program has built-in the list of the acceptable tire data files. The source libraries can be modified using a word processor. A useful feature was the record counter at the beginning of the directory helping the retrieval, search, display and updating of the tire files. The directory provided information about the record number, tire size, tire ply rating and tire type. The tire data file provided information about rated inflation pressure, rated load, static loaded radius, overall diameter and tire section width. Two limitations were that the source file should be an ASCII file and that the source file format should be compatible with the program's internal pattern.

---

[4] ASCII: American Standard Code for Information Interchange

The inspection of the tire data files was also possible. The power of this utility became obvious when an error message concerning available tire information was displayed during tractor data processing. During file read the tire records were read bidirectionally using the keypad keys. The counter located at the beginning of the directory file and the internal record counter provided information about the "where" with respect to the boundaries. Wraparound at both file boundaries was implemented. During record searching the tire size and the ply rating were requested. If the ply rating was not specified, the first occurrence of matching tire sizes was displayed. If no matching tire sizes were found an error message was displayed. No interrupt was implemented.

If the user wished to provide new tire information, the files USER.DIR and USER.RND were available in the diskette.

#### 7.5.9.3. File management utility

The file management utility facilitated four basic functions of file handling from within the software. The functions were Copy, Rename, Create and Delete files. Upon selection of a function a window was opened providing a menu to enter the appropriate information. Immediate program interrupt was implemented. If destructive file operation was to be executed the user would have been questioned to verify the operation.

#### 7.5.9.4. User defined program

The user defined program option provided a pointer to the memory location 90000H, where a user program can be loaded.

### 7.6. Conclusions

In conclusion, the program is user friendly, facilitating on-line help, is fast due to Compilation and Assembly language programming and is conveniently integrated through a hierarchical Database Management System.

Among the limitations of the program is the inability to handle more than one file at a time and the inability to perform regression analysis on large numbers, such as RPM.

The fact that the program contains three models and is easy-to-learn-and-use can make it a good educational aid.

# 8. SUMMARY AND CONCLUSIONS

Three in-soil tractor performance prediction models were developed and presented. The models were developed using off-the-shelf equations, modified or extended as required, in order to be complete and take into account dynamic parameters, such as calculated weight transfer.

The models were analyzed and compared in terms of travel reduction or slip, Drawbar Pull, Pull or Dynamic Traction Ratio and Tractive Efficiency. Commenting on the models, the following can be stated:

a. The ASAE D230.4 model was originally designed by Zoz (1972) for 2WD tractor in-soil performance prediction. The model can be applied, with caution, to 4WD tractors by considering equivalent parameters applicable to both front and rear traction devices. The model gave poor results with FWA tractors.

b. The OECD model was originally designed as an all-tractor static analysis method, using empirical equations as a function of the Mobility Number. The modification of the original model by the author, through the introduction of the calculated weight transfer was not successful. The reasons for model inbalance were related to the invalidity of the empirical equations under non-static conditions.

c. The HELLAS model was built around the Wismer and Luth (1974) equation for Pull Ratio calculation. The model was designed for all-tractor in-soil dynamic performance analysis. The fact that the Wismer and Luth equation is a function of the soil Cone Index and also applies to a traction device makes the model suitable for all-tractor analysis with no limitations.

For the calculation of the moments around the rear axle, the static tire radius was replaced by the tire effective arm, which in the literature can be found as tire rolling radius. The importance of the substitution of the static tire radius with the tire effective arm in the calculations is shown in the equation giving Torque Ratio, presented by Wismer and Luth. The implementation of the model was made possible using tire load-deflection curves, supplied by the tire companies.

The integrated software presented in this study was developed with the perspective of portability, universality, user friendliness and integration. The integrated software was developed to accommodate three in-soil tractor performance prediction models using a desktop microcomputer.

A menu-driven hierarchical DBMS was developed around the models for the needs of the software. The introduction of random access files and directories considerably enhanced application power. The tractor analysis aimed in data preparation consisted of the calculation of the tractor characteristics on the driving axle, in order to establish the tractor as a "black box". The tractor analysis algorithm was reliable. The prediction models were developed using off-the-shelf equations.

The hardware capabilities of the IBM PC in terms of numerical and graphics processing were limited. The statistical analysis, even though double precision numbers were used, was not as accurate as it would be in a large computer. However, for the purpose of the application the accuracy of the results was adequate. The graphical representation of various tractor performance relationships, either using high or low resolution screen, gave an advantage to the application.

Program integration made possible the sharing of information among the various routines of the program. The successful handling of information was based on the capability of the program to access individual fields and records of the random access tractor database files for read and write operations.

User friendliness was promoted identifying each stage in the tree-structure of the DBMS through unified menus and easy option selection implemented on meaningful keys. In addition, the on-line help was a significant feature, increasing user friendliness.

The compilation of the program made a number of features possible. The two most important were the capability of the program to exceed the logical limit of the

64 K imposed by the BASIC Interpreter and the improvement of the execution speed up to twenty times. Assembly language programming considerably enhanced the scope of the integrated software.

The overall performance of the software remains to be evaluated by the user. If an in-soil tractor performance prediction model is to be selected for further software development, the HELLAS model which was based on the Wismer and Luth equation, should be selected.

# 9. RECOMMENDATIONS FOR FURTHER WORK

## 9.1. Introduction

The recommendations for further work fall into the following three categories:

a. programming techniques;

b. program scope;

c. experimental verification of the models.

## 9.2. Programming techniques

In order to increase program power the following features should be implemented:

a. Allocation of an appropriate size buffer in the memory to facilitate simultaneous display of more than one tractor file at a time.

b. Combination of the existing menus with the concept of the Window, taking advantage of the Mouse capabilities. The purpose of this modification is to enhance user friendliness.

## 9.3. Program scope

In order to broaden the scope of the software the following features should be incorporated.

a. Introduction of fuel consumption information from the Nebraska Tractor Test report.

b. Introduction of implement information. The information can be used by the models for in-soil tractor performance prediction using a particular implement, field capacity calculation or tractor-implement matching optimization.

c. Introduction of an algorithm simulating field operation (timeliness, yield, etc.) when implement and field pattern information are provided.

### 9.4. Model experimental verification

The in-soil tractor performance prediction models were developed using off-the-shelf relationships.

Two areas requiring further research are the proper calculation of the tire effective arm during in-soil tractor operation and the development of an equation to relate rolling resistance coefficient with tire size and soil strength.

Experimental in-soil model verification is essential and can be obtained using an on-tractor single-board microcomputer connected to a number of transducers installed in appropriate locations of the tractor.

Two key factors that require further development are soil strength and bearing capacity. The soil Cone Penetrometer is currently the most convenient way to obtain *in situ* evaluation of the soil strength, in order to use this information in a trafficability analysis. However, Cone Index measurements with the soil Cone Penetrometer constitute a weak link of the in-field tractor performance prediction analysis and for that reason require further standardization of the sampling methods and better interpretation of the results.

## REFERENCES

### Abreviations

AE : Agricultural Engineering, Journal of the ASAE
AES : Agricultural Engineering Society, England
ASAE : American Society of Agricultural Engineers
CAE : Canadian Agricultural Engineering
CSAE : Canadian Society of Agricultural Engineering
JAER : Journal of Agricultural Engineering Research
JT : Journal of Terramechanics
NIAE : National Institute of Agricultural Engineering
SAE : Society of Automotive Engineers
Trans : Transactions of the ASAE

## LIST OF REFERENCES

1. Adsit A.H. and R.L. Clark. 1983. Wheel-to-Wheel Variability in Slip on a Four-Wheel Drive Tractor. ASAE Paper no. 83-1054, St. Joseph, MI
2. Alberta Agriculture. 1983. Radial Tires for Agricultural Tractors. Agrifax, Agdex 740-1, Edmonton, AB
3. American Association for State Highway and Transportation Officals. 1978. Standard Specifications for Transportation Materials and Methods of Sampling and Testing. 12th Ed., Part I- Specifications, Part II-Tests. Washington, DC
4. American Society for Testing and Materials. 1980. Natural Building Stones; Soil and Rock. Annual Book of ASTM Standards. Part 19, Philadelphia, PA
5. American Society of Agricultural Engineers. © 1984. Standards. St. Joseph, MI
6. Amir I., G.S.V. Raghavan, E. McKyes and R.S. Broughton. 1976. Soil Compaction as a Function of Contact Pressure and Soil Moisture. CAE 18:54-57, Ottawa, ON
7. Anonymous. 1975. How Good are Tractor Radial Tires? AE, June 1975:762-763, St Joseph, MI

8. Ayers P.D and J.V. Perumpral. 1982. Moisture and Density Effect on Cone Index. ASAE Trans 25(5): 1169-1172, St. Joseph, MI

9. Ayers P.D. and H.D. Bowen. 1983. Predicting Soil Density Profiles using Cone Penetration Resistance. ASAE Paper no. 83-1051, St. Joseph, MI

10. Bailey A.C. and J.A. Weber. 1965. Comparison of Methods of Measuring Soil Shear Strength Using Artificial Soils. ASAE Trans 8(2):153-156, St. Joseph, MI

11. Bashford L.L. 1975. Wheel Weights: How Much? NebGuide, G 76-287, University of Nebraska, Lincoln, NE

12. Bashford L.L. 1976. How Many Drawbar Horsepower Can Your Tractor Develop? NebGuide G76-287, University of Nebraska, Lincoln, NE

13. Bashford L.L. 1984. Power Losses Due to Slip and Motion Resistance. ASAE Paper no. 84-1564, St. Joseph, MI

14. B.F.Goodrich. Farm Tire Data Book. Akron, OH

15. Bekker M.G. 1956. Theory of Land Locomotion. University of Michigan Press. Ann Arbor, MI

16. Bernstein R. 1913. Problems zur experimentellen motorpflugmechanick. Der Motorwagen, Vol 16

17. Bishop A.W. and D.J. Henkel. 1962. The measurement of Soil Properties in the Triaxial Test. 2nd Ed. Edward Arnold Ltd., London, UK

18. Bloome P.D., A. Khalilian, G.P. Rietmuller and D.G. Batchelder. 1982. Demonstrating the Effect of Ballast in Tractor/Implement Matching. ASAE Paper no. 82-1054, St. Joseph, MI

19. Bloome P.D., J.D. Summers, A. Khalilian and D.G. Batchelder. 1983. Ballasting Recommendations for Two-Wheel and Four-Wheel Drive Tractors. ASAE Paper no. 83-1067, St. Joseph, MI

20. Bohnert L.F. and T.D. Kenady. 1975. A Compactive Analysis of Radial and Bias R-1 Drive Wheel Tractor Tires. SAE Paper no. 751185, Moline, IL

21. Bowen H.D., H. Jaafari and P.D. Ayers. 1984. An Application of Boussinesq's Equation to Soil Dynamics. ASAE Paper no. 84-1049, St. Joseph, MI

22. Brixius W.W. and R.D. Wismer. 1978. The Role of Slip in Traction. ASAE Paper no. 78-1538, St. Joseph, MI

23. Buck N.L., D.H. Vanghan and H.A. Hughes. 1984. A General-Purpose Simulation Model for Agricultural Applications. ASAE Paper no. 84-5515, St. Joseph, MI

24. Burt E.C. and A.C. Bailey. 1981. Interaction of Dynamic Load and Inflation Pressure on Tire Performance. ASAE Trans 25(4):881-884, St. Joseph, MI

25. Burt E.C. and P.W.L. Lyne. 1983. Velocity Effects on Traction Performance. ASAE Paper no. 83-1556, St. Joseph, MI

26. Burt E.C., P.W.L. Lyne, P. Meiring and J.F. Keen. 1983. Ballast and Inflation Pressure Effects on Tire Efficiency. ASAE Trans 26(5):1352-1354, St. Joseph, MI

27. Burt E.C., J.H. Taylor and L.G. Wells. 1984. Traction Characteristics of Prepared Traffic Lanes. ASAE Paper no. 84-1031, St. Joseph, MI

28. Burt E.C., R.K. Wood and A.C. Bailey. 1984. A 3-Dimensional System for Measuring Tire Deflections. ASAE Paper no. 84-1553, St. Joseph, MI

29. Campbell D.J. and J.W. Dickson. 1984. Effect of Four Alternative Front Tyres on Seedbed Compaction by a Tractor Fitted with a Rear Wheel to Minimize Compaction. JAER, No.24, pp. 83-91, Cambridge, UK

30. Canadian Alternate Fuels. 1983. Special publication of the Biomass Energy Institute. Winnipeg, MB

31. Carnegie E.J., R.R. Grinvel and N.A. Richardson. 1983. Personal Computer for Measuring Tractor Performance. ASAE Paper no. 83-1065, St. Joseph, MI

32. Carpenter T.G. and N.R. Fausey. 1983. Tire Sizing for Minimizing Subsoil Compaction. ASAE Paper no. 83-1058, St. Joseph, MI

33. Carper R.L. and A.E. Opp. 1977. Tire performance on a Four-Wheel Drive Tractor. ASAE Paper no. 77-1518, St. Joseph, MI

34. Chancellor W.J. and N.C. Thai. 1983. Automatic Control of Tractor Engine Speed and Transmission Ratio. ASAE Paper no. 83-1061, St. Joseph, MI

35. Charles S.M. 1983. Load and Pressure Effects on Radial Tire Traction Performance. ASAE Paper no. 83-1557, St. Joseph, MI

36. Charles S.M. and D.J. Schuring. 1984. An Empirical Model for Predicting the Effective Rolling Radius of Agricultural Drive Tires. ASAE Paper no. 84-1555, St. Joseph, MI

37. Charles S.M. 1975. Firestone Tire & Rubber Company. Personal communication.

38. Colvin T.S., K.L. McConnell and B.J. Catus. 1984. A Computer Model for Field Simulation. ASAE Paper no. 84-1523, St. Joseph, MI

39. Cook R. 1984. Conquering Computer Clutter. High Technology. Vol.4, No.12:60-70, December 1984, Boston, MA

40. Cromer W.A. and B.D. McLendon. 1984. Microprocessor-Based Radio Telemetry System for Determination of Soil Moisture Status. ASAE Paper no. 84-1593, St. Joseph, MI

41. Davis D.C. and J.R. Cooke. 1983. "Friendly" Finite Element Analysis. ASAE-CSAE Paper no. PNR/83-105, St. Joseph, MI

42. Domier K.W. and O.H. Friesen. 1969. Performance Parameters of Tractors Equipped with Singles, Duals and Four-Wheel Drive. CAE 11(1):16, Ottawa, ON

43. Domier K.W., O.H. Friesen and J.S. Townsend. 1971. Traction Characteristics of Two-Wheel Drive, Four-Wheel Drive and Crawler. ASAE Trans 14(3):520, St. Joseph, MI

44. Domier K.W. and S.P.E. Persson. 1968. Comparison of Predicted and Measured Drawbar Performance of Tractors on Agricultural Soils. CAE 10(1):29-32, Ottawa, ON

45. Domier K.W. and A.E. Willans. 1978. Maximum or Optimum Tractive Efficiency? ASAE Trans 21(4):650-653, St. Joseph, MI

46. Domier K.W. 1978. Traction Analysis of Nebraska Tractor Tests. ASAE Trans, 21(2):244-248, 1978, St. Joseph, MI

47. Domier K.W. and A.E. Willans. 1979a. Prediction of Drawbar Power - Several Approaches. ASAE Paper no. 79-1551, St. Joseph, MI

48. Domier K.W. and A.E. Willans. 1979b. 2WD vs. 2WD Add-Ons vs. 4WD Tractors. Agriculture and Forestry Bulletin, 2(2):14-16, University of Alberta, Edmonton, AB

49. Dunlap W.H., G.E. Vanden Berg and J.G. Hendrick. 1966. Comparison of Soil Shear Values Obtained with Devices of Different Geometrical Shapes. ASAE Trans 9(6):896-900, St. Joseph, MI

50. Dwyer M.J., D.R. Comely and D.W. Evernden. 1974a. The Development of a Handbook of Agricultural Tyre Performance. NIAE DN/T/517/1415, UK

51. Dwyer M.J., D.R. Comely and D.W. Evernden. 1974b. Handbook of Agricultural Tyre Performance. NIAE Report no. 14, UK

52. Dwyer M.J. 1975. Some Aspects of Tyre Design and their Effect on Agricultural Tractor Performance. JAER 204775, UK

53. Dwyer M.J. and G. Pearson. 1975. A Field Comparison of the Tractive Performance of Two and Four-Wheel Drive Tractors. NIAE DN/T/574/1405, Silsoe, UK

54. Dwyer M.J. and D.P. Heigho. 1984. The Tractive Performance of some Large Tractor Drive Wheel Tyres Compared with Dual Wheels. JAER, No.29:43-50, Cambridge, UK

55. Dwyer T. and M. Critchfield. ® 1978. BASIC and the Personal Computer. Microcomputer Books, Addison-Wesley Publishing Company, Don Mills, ON

56. Ellis R.W. 1985. GOODYEAR Tire & Rubber Company. Personal communication.

57. Erickson L.R. and W.E. Larsen. 1983. Four-Wheel Drive Tractor Performance. ASAE Trans 26(5)1346-1351, St. Joseph, MI

58. Firestone. Farm Tire Data and Information. Akron, OH

59. Freitag D.R. 1965. Wheels on Soft Soils. An Analysis of Existing Data. US Army Engineer Waterways Experiment Station, Technical Report no. 3-670, Vicksburg, MS

60. Freitag D.R. and M.E. Smith. 1966. Center-line Deflection of Pneumatic Tires Moving in Dry Sand. JT 3(1):31-46, Oxford, UK

61. Freitag D.R. 1968. Penetration Tests for Soil Measurements. ASAE Trans 11(6):750-753, St. Joseph, MI

62. Gameda S., G.S.V. Raghavan, R. Theriault and E. McKyes. 1984. High Axle Load Compaction Effect on Stress and Subsoil Density. ASAE Paper no. 84-1547, St. Joseph, MI

63. Garber M. and D. Wolf. 1984. Track-Soil Interaction for Maximum Tractive Effort. JAER, No. 29:191-198, Cambridge, UK

64. Gill W.R. and G.E. Vanden Berg. 1967. Soil Dynamics in Tillage and Traction.Agricultural Handbook No. 316. United States Department of Agriculture, Washington, DC

65. Göhlich H. 1984. The Development of Tractors and other Agricultural Vehicles. JAER, No. 29:3-16, Cambridge, UK

66. GOODYEAR. Farm Tire Data Book. Akron, OH

67. Green M.K., B.A. Stout and S.W. Searcy. 1983. Instrumentation Package for Monitoring Tractor Performance. ASAE Paper no. 83-1562, St. Joseph, MI

68. Harrison H.P. 1970. Ballast for OI L 1imum Tractive Performance. CAE 12(3):12-17, Ottawa, ON

69. Hauck D., V. Hofman and H. Kucera. 1984. Traction - Horsepower Demonstration. ASAE Paper no. 84-1061, St. Joseph, MI

70. Hausz F.C. and H. Akins. 1980. OI L 1imizing Tire-Vehicle Relationships for Best Field Performance. SAE Paper no. 801021, Warrendale, PA

71. Hemingway P.F., J.S. Price and J.D. Scott. 1982. A System to Control Tractor Tyre Inflation Pressure On-The-Move. AE, Winter 1982:109-111, St. Joseph, MI

72. Hendrick J.K., C.E. Johnson, R.L. Schafer and J.D. Jarrel. 1981. A Microprocessor-Based Field Data Acquisition System. ASAE Paper no. 81-1577, St. Joseph, MI

73. Hoemsen R. 1984. Structural Design of Agricultural Wheels. ASAE Paper no. 84-1558, St. Joseph, MI

74. Holtz R.D. and W.D. Kovacs. © 1981. An Introduction to Geotechnical Engineering. Prentice-Hall, Inc., Englewood Cliffs, NJ

75. Inns F.M. and J. Kilgour. © 1978. Agricultural Tyres. Brown Knight and Truscott Ltd, London and Tonbridge, UK

76. International Business Machines (IBM). © 1983. BASICA. International Business Machines Corporation, Boca Raton, FL

77. International Business Machines (IBM). © 1983. Disk Operating System. International Business Machines Corporation, Boca Raton, FL

78. International Business Machines (IBM). © 1981,1982,1983. Technical Reference. International Business Machines Corporation, Boca Raton, FL

79. John Deere. 1979a. Fundamentals Of Service (FOS). Engines. Deere & Company, Moline, IL

80. John Deere. 1979b. Fundamentals Of Service (FOS). Power Trains. Deere & Company, Moline, IL

81. Johnson C.E., D.W. Wright and A.C. Bailey. 1983. Compaction Characteristics of Some Soil Mixtures. ASAE Trans 26(5):1337-1339, St. Joseph, MI

82. Johnson C.E., A.C. Bailey, T.A. Nichols and R.D. Grisso. 1984. Soil Behavior Under Repeated Hydrostatic Loading. ASAE Paper no. 84-1548, St. Joseph, MI

83. Jurek R.L. and B.C. Newendorp. 1983. In-Field Fuel Efficiency Comparisons of Various John Deere Tractors. ASAE Paper no. 83-1563, St. Joseph, MI

84. Kenady T.D. 1985. BFGoodrich Company, Tire Group. Personal communication.

85. Khalilian A., D.G. Batchelder, K. Self and J.D. Summers. 1984. Revision of Fuel Consumption Equations for Diesel Tractors. ASAE Paper no. 84-1522, St. Joseph, MI

86. Kline E. and J.V. Perumpral. 1984. A Computer Model for Predicting Tractor Load Effects on Soil Stress. ASAE Paper no. 84-1545, St. Joseph, MI

87. Knight S.J. and D.R. Freitag. 1962. Measurement of Soil Trafficability Characteristics. ASAE Trans 5(2):121-132, St. Joseph, MI

88. Knight S.J. and A.J. Green. 1962. Deflection of a Moving Tire on Firm to Soft Surfaces. ASAE Trans 5(2):116-120, St. Joseph, MI

89. Kotzabassis C. and K.W. Domier. 1985. An Approach for In-Soil Tractor Performance Prediction. ASAE Paper no. 85-1555, St. Joseph, MI

90. Kotzabassis C., A.W. Anderson and K.W. Domier. 1985. High Efficiency Tractor Analysis-Simulation Software. ASAE Paper no. 85-1556, St. Joseph, MI

91. Kraft G.D. and W.N. Toy. © 1979. Mini/Microcomputer Hardware Design. Prentice Hall, Inc., Englewood Cliffs, NJ

92. Kranzler G.A. 1984. Digital Image Processing for Agriculture. ASAE Paper no. 84-5513, St. Joseph, MI

93. Larsen L. © 1981. Farm Tractors 1950-1975. ASAE, St. Joseph, MI

94. Leviticus L.I. and J.F. Reyes. 1983a. Traction on Concrete - I. Dynamic Ratio and Tractive Quotient. ASAE Paper no. 83-1558, St. Joseph, MI

95. Leviticus L.I. and J.F. Reyes. 1983b. Traction on Concrete - II. Tractive Efficiency. ASAE Paper no. 83-1559, St. Joseph, MI

96. Liljedahl J.B., W.M. Carleton, P.K. Turnquist and D.W. Smith. © 1979. Tractors and their Power Units. Third Edition. John Wiley & Sons, Inc., New York., NY

97. Lu C. 1984. Integrated Software Bids the Center Stage. High Technology, Vol.4, No.11:32-44, November 1984, Boston, MA

98. Lyne P.W.L., E.C. Burt and P. Meiring. 1982. Wheel Ballast for Improved Specific Fuel Consumption. ASAE Paper no. 82-1568, St. Joseph, MI

99. MacEwan G. © 1974. Power for Prairie Plows. Western Producer Book Service, Saskatoon, SK

100. Marvin J.P. 1984. Introduction to Digital Math. ASAE Paper no. 84-5509, St. Joseph,MI

101. Mayko J.J. and K.W. Domier. 1984. Another Twist to Front Wheel Assist. ASAE Paper no. PNR 84-103, St. Joseph, MI

102. McKibben E.G. 1938. Some Kinematic and Dynamic Studies of Rigid Transport Wheels for Agricultural Equipment. Iowa State University. Agricultural Experiment Station, Research Bulletin, no. 231

103. McKinion J.M. 1984. Microcomputers, Data Acquisition, Control and the IEEE-488 Bus. ASAE Paper no. 84-5528, St. Joseph, MI

104. McLaren P., C.V. Narayan and J.K. Blundell. 1983. Further Developments in Predicting Agricultural Tractor Performance. ASAE Paper no. 83-1069, St. Joseph, MI

105. Micklethwait E.W.E. 1944. Tracks for Fighting Vehicles. School of Tank Technology. Vicksbourg, MS

106. Morling R.W. 1982. The Pros and Cons of "Controlled Traffic" Farming. ASAE Paper no. 82-1043, St. Joseph, MI

107. Mortensen D.G. 1982. Wheeled Vehicle Traction Performance. ASAE Paper no. 82-1043, St. Joseph, MI

108. Mulqueen J., J.V. Stafford and D.W. Tanner. 1976. Evaluation of Penetrometers for Measuring Soil Strength. NIAE DN/T/738/1162, UK

109. Musonda N.G., F.W. Bigsby and G.C. Zoerb. 1983. Four Wheel Drive Tractor Instrumentation for Traction Studies. ASAE Paper no. 83-1554, St. Joseph, MI

110. Nichols T.A., A.C. Bailey, C.E. Johnson and R.D. Grisso. 1984. A Stress State Transducer for Soil. ASAE Paper no. 84-1592, St. Joseph, MI

111. Organization for Economic Co-operation and Development. 1984. OECD Standard Codes for the Official Testing of Agricultural Tractors and Protective Structures - Predicting Tractor Field Performance from Test Data. AGR/TS(84)9, Paris, F

112. Pacey D.A., G.M. Dowell and R.E. Welty. 1984. Tractor Efficiency Demonstrations in Kansas.ASAE Paper no. 84-1060, St. Joseph, MI

113. Pang S.N., G.C. Zoerb and G. Wang. 1984. A Tractor Performance Monitor Based on an Indirect Method of Fuel Consumption Measurement. ASAE Paper no. 84-1059, St. Joseph, MI

114. Persson S.P.E. 1967. Parameters for Tractor Wheel Performance. Part I - Definitions. ASAE Trans 10(3): 420-423, St. Joseph, MI

115. Perumpral J.V. and Desai C.S. 1979. A Generalized Model for a Soil-Tillage Tool Interaction. ASAE Paper no. 79-1546, St. Joseph, MI

116. Peters B.L. 1983. Weight Transfer Analysis on Four-Wheel Drive Tractors. ASAE Paper no. 83-1068, St. Joseph, MI

117. Pitts M.J. 1984. Introduction to Digital Math. ASAE Paper no. 84-5509, St. Joseph, MI

118. Raghavan G.S.V. and E. McKyes. 1977a. Study of Traction and Compaction Problems of Eastern Canadian Agricultural Soils. Department of Agricultural Engineering. McGill University, Montreal, PQ

119. Raghavan G.S.V. and E. McKyes. 1977b. Laboratory Study to Determine the Effect of Slip-Generated Shear on Soil Compaction. CAE 19(1):40-42, Ottawa, ON

120. Rector R. and G. Alexy. © 1980. The 8086 Book. OSBORNE/ McGraw Hill., Berkeley, CA

121. Reece A.K. 1964. Theory and Practice of the Off-The-Road Locomotion. AES Annual Conference. London, UK

122. Reece A.R. 1964. Problems of Soil Vehicle Mechanics. US Army Tank-Automotive Center, Warren, MI

123. Reece A.R. 1967. Tractor Design and Tractive Performance. AES, Paper no. 3/4/E/34, Bedford, UK

124. Renius K.T. 1979. European Four-Wheel Drive: Are Technical Advantages Profitable? ASAE Paper no. 79-1555, St. Joseph, MI

125. Richardson N.A., R.L. Lanning, K.A. Kopp and E.J. Carnegie. 1983. True Ground Speed Measurement. ASAE Paper no. 83-1059, St. Joseph, MI

126. Riethmuller P., D.G. Batchelder and P.D. Bloome. 1983. A Microcomputer System for Cone Index Measurement. ASAE Trans 26(4):996, St. Joseph, MI

127. SAE Task Force - Final Report. 1978. Prediction of Traction on Concrete. Warrendale, PA

128. Searcy S.W. and D.A. Ahrens. 1983. Making Your Tractor Talk. (Implementation of Speech Synthesis). ASAE Paper no. 83-1089, St. Joseph, MI

129. Shropshire G.J., G.R. Woerman and L.L. Bashford. 1983. A Microprocessor Based Instrumentation System for Traction Studies. ASAE Paper no. 83-1048, St. Joseph, MI

130. Smith D.W., R.A. Light, B.E. Roming, T.A. Berenyi, N.V. Orlandea, J.C. Wiley, N. Portillo, S.E. O'Brien and D.J. Hertema. 1982. Automated Simulation and Display of Mechanism and Vehicle Dynamics. ASAE Paper no. 82-5019, St. Joseph, MI

131. Smith D.W. 1984. The Influence of Drawbar Position on Tractor Rearward Stability. ASAE Paper no. 84-1560, St. Joseph, MI

132. Smith L.A. 1984. Automatic Control of Tractor Engine Speed. ASAE Paper no. 84-1595, St. Joseph, MI

133. Society of Automotive Engineers. 1984. Handbook. On-Highway Vehicles and Off-Highway Machinery. Volume 4. Society of Automotive Engineers, Inc., Warrendale, PA

134. Speckhart F.H. and W.L. Green. © 1976. A Guide Using CSMP - The Continuous System Modeling Program. Prentice-Hall, Inc., Englewood Cliffs, NJ

135. Steel R.G.D. and J.H. Torrie. 1980. Principles and Procedures of Statistics. A Biometrical Approach. McGraw-Hill, Inc., Montreal, PQ

136. Strayer R.C. and W.K. Craig. 1983. Vegetable Oils as Diesel Fuel. Department of Agricultural Emngineering. University of Saskatchewan, Saskatoon, SK

137. Sudduth K.A. 1984. Computer Analysis of the Three-Point Hitch. ASAE Paper no. 84-5522, St. Joseph, MI

138. Summers J.D. 1983. Performance Simulation of Two-Wheel Drive and Four-Wheel Drive Tractors. PhD Thesis. University Microfilms International, no. 8404850, Ann Arbor, MI

139. Summers J.D., P.E. Ekstrom and K. Von Bargen. 1983. Development of a Tractor Performance Simulation Model. ASAE paper no. 83-1561, St. Joseph, MI

140. Summers J.D. and K. Von Bargen. 1983. A Simplified Tractor Performance Simulation Model. ASAE Paper no. 83-1564, St. Joseph, MI

141. Taylor D.W. © 1948. Fundamentals of Soil Mechanics, John Wiley & Sons, Inc., New York, NY

142. The Tire and Rim Association, Inc. © 1984. Yearbook. Akron, OH

143. Tollner E.W. and R.L. Clark. 1984. Field Performance of a Lubricated and Conventional Cone Penetrometer. ASAE Paper no. 84-1549, St. Joseph, MI

144. Townsend J.S., K.W. Domier and N.C. Garg. 1971. Traction Characteristics of an Agricultural Tractor. ASAE Paper no. 71-134, St. Joseph, MI

145. Turnage G.W. 1976. In-Soil Towing Resistance of Selected Radial and Bias-Ply Tires. ASAE Paper no. 76-1035, St. Joseph, MI

146. Upadhyaya S.K. 1984. Prediction of Tillage Implement Draft. ASAE Paper no. 84-1518, St. Joseph, MI

147. Upadhyaya S.K and F. Shafigh-Nobari. 1984. Interaction Between Soil and Low-Pressure Pneumatic Tire Interaction. ASAE Paper no. 84-1556, St. Joseph, MI

148. Upadhyaya S.K., R. Hamidi, F. Shafigh-Nobari and R.W. Hooley. 1984. Tractive Ability of Pneumatic Tires: A Finite Element Model. ASAE Paper no. 84-1052, St. Joseph, MI

149. Upadhyaya S.K., L.J. Kemble, N.E. Collins and T.H. Williams. 1982. Cone Index Prediction Equations for Delaware Soils. ASAE Paper no. 82-1542, St. Joseph, MI

150. U.S. Army Corps of Engineers. 1970. Laboratory Soils Testing. Engineer Manual, EM 1110-2-1906. Vicksbourg, MI

151. U.S. Army Engineer Waterways Experiment Station. 1960. "The Unified Soil Clasification System", Technical Memorandum No. 3-357. Appendix A-Characteristics of Soil Groups Pertaining to Embankments and Foundations (1953), Appendix B-Characteristics of Soil Groups Pertaining to Roads and Airfields (1957). Vicksbourg, MS

152. U.S. Bureau of Reclamation. 1974. Earth Manual, 2nd Ed., Denver, CO

153. Van Riemsdijk J.T. and K. Brown. © 1980. The Pictorial History of Steam Power. Octopus, London, UK

154. VanGerpen H.W. and R.L. Mayfield. 1982. Dyna Cart - A Programmable Drawbar Dynamometer for Evaluating Tractor Performance. ASAE Paper no. 82-1056, St. Joseph, MI

155. Volfson B.P. 1983. Determination of Soil Properties for Vehicle Ride Simulation. ASAE Paper no. 83-1049, St. Joseph, MI

156. Wells L.G. and E.C. Burt. 1984. Response of Selected Soils to Powered Tires at Disparate Moisture Conditions. ASAE Paper no. 84-1540, St. Joseph, MI

157. Wells L.G. and C.O. Lewis. 1980. Remote Electronic Acquisition of Soil Cone Index Measurements. ASAE Paper no. 80-5024, St. Joseph, MI

158. Whittaker A.D., D.E. Guyer and G.E. Miles. 1984. An Introduction to Digital Image Processing. ASAE Paper no. 84-5510,St. Joseph, MI

159. Wilhelm L.R. and J.B. Wilkerson. 1984. Use of Lotus 1-2-3 on the IBM PC for Agricultural and Engineering Applications. ASAE Paper no. 84-5517, St. Joseph, MI

160. Wismer R.D. and H.J. Luth. 1972. Performance of Plane Soil Cutting Blades in Clay. ASAE Trans 15(2):211-216, St. Joseph, MI

161. Wismer R.D. and H.J. Luth. 1974. Off-Road Traction Prediction for Wheeled Vehicles. ASAE Trans 17(1):8-16, St. Joseph, MI

162. Wismer R.D. 1982. Soil Dynamics: A Review of Theory and Application. SAE Paper no. 820656, Warrendale, PA

163. Wismer R.D. 1984. Soil Bin Facilities: Characteristics and Utilization. Deere & Company, Technical Center, Moline, IL

164. Witney B.D. 1983. Power Demand Prediction from Climate Variables. ASAE Paper no. 83-1057, St. Joseph, MI

165. Woerman G.R. and L.L. Bashford. 1983. Performance of a Front Wheel Assist Tractor. ASAE Paper no. 83-1560, St. Joseph, MI

166. Wolfe P.M. and C.P. Koelling. 1983. BASIC Engineering and Scientific Programs for the IBM PC. Prentice-Hall, Inc., Scarborough, Ont.

167. Wolkerton V. © 1984. Running MS-DOS. Microsoft Press. Bellevue, WA

168. Wood R.K and L.G. Wells. 1984. The Effect of Wheel Pull on the Estimation of Soil Stress. ASAE Paper no. 84-1046, St. Joseph., MI

169. Yong R.N. and Fattah E.A. 1976. Prediction of wheel Soil Interaction and Performance Using the Finite Element Method. JT, Vol 13, Oxford, UK

170. Yong R.N. and A.W. Hanna. 1977. Finite Element Analysis of Plane Soil Cutting. JT, Vol 14, Oxford, UK

171. Yong R.N., E.A. Fattah and P. Boonsinsuk. 1978. Analysis and Prediction of Type-Soil Interaction and Performance Using Finite Elements. JT, Vol 15, Oxford, UK

172. Young S.C., C.E. Johnson and R.L. Schafer. 1983. A Vehicle Guidance Controller. ASAE Trans 26(5):1340-1345, St. Joseph, MI

173. Zhang N., J.B. Liljendahl and G.E. Miles. 1984. Slip Control of Hydrostatically Driven Wheels. ASAE Paper no. 84-1053, St. Joseph, MI

174. Zoz F.M. 1972. Predicting Tractor Field Performance. ASAE Trans 15(2):249-255, St. Joseph, MI

175. Zoz F.M. and W.W. Brixius. 1979. Traction Prediction for Agricultural Tires on Concrete. ASAE Paper no. 79-1046, St. Joseph, MI

# APPENDIX A

# GENERAL INFORMATION

## Table A.1

Standards, Data and Engineering Practices

(ASAE Standards 1984)

| | |
|---|---|
| ASAE S203.10 | (SAE J1170), Rear Power Take-Off for Agricultural Tractors. (rel.; ANSI/ ASAE S331.3) |
| ASAE S205.2 | (SAE J722), Power Take-Off (PTO) Definitions and Terminology for Agricultural Tractors. (rel.: ASAE S333.1) |
| ASAE S207.10 | (SAE J721), Operating Requirements for Tractors and Power Take-Off Driven Implements. |
| ASAE S209.5 | (SAE J708), Agricultural Tractor Test Code. (ref.: Table A.4) |
| ASAE S219.2 | (SAE J712a), Agricultural Tractor and Equipment Disc Wheels. (rel.: ASAE S218.2) |
| ASAE S220.4 | (SAE J711c), Tire Selection Tables for Agricultural Machines of Future Design. (rel.: TRA 1984 Yearbook) |
| ASAE D230.4 | Agricultural Machinery Management Data (This ASAE Data source was the guideline for one of the computer models) |
| ASAE EP291.1 | Terminology and Definitions for Soil Tillage and Soil-Tool Relationships. |

Table A.1 (Cont'd)

| | |
|---|---|
| ASAE S295.2 | (SAE J709d), Agricultural Tractor Tire Loadings, Torque Factors and Inflation Pressures. |
| ASAE S296.2 | Uniform Terminology for Traction of Agricultural Tractors, Self Propelled Implements and Other Traction and Transport Devices. |
| ASAE S346.1 | (SAE J884) Liquid Ballast Table for Drive Tires of Agricultural Machines. |
| ASAE S390.1 | (SAE J1150) Classifications and Definitions of Agricultural Equipment. |
| ASAE EP391.1 | Agricultural Machinery Management. |
| ASAE S414 | Terminology and Definitions for Agricultural Tillage Implements. (rel.: ASAE S338.1) |

## Table A.2

Agricultural Tractor Test Code (ASAE S209.5)

(ASAE Standards 1984)

A. Test Conditions

B. Detailed Description of Test Procedure

  B.1 Preparation of tractor for performance runs

  B.2 Mechanical power outlet performance

    B.2.1 Maximum power-fuel consumption

    B.2.2 Varying power-fuel consumption

    B.2.3 Power at standard Power Take-Off speed

  B.3 Drawbar performance

    B.3.1 Maximum drawbar performance

    B.3.2 Varying drawbar power-fuel consumption including sound level at operator station

    B.3.3 Drawbar pull versus travel speed

    B.3.4 Exterior sound level

C. Final Inspection

D. Calculations and Formulas

E. Definition of Terms

F. Uniform Method of Publishing Results.

## Table A.3

Approved Procedure for Rounding Data

(The Tire and Rim Association Inc., Yearbook 1984)

| Measurement | Customary unit | SI unit | Conversion factor | Accuracy |
|---|---|---|---|---|
| Dimensions | inch (in) | millimeter (mm) | mm=25.4*in | nearest 0.1 mm* |
| Distance | mile (mi) | kilometer (km) | km=1.609*mi | nearest km |
| Load | pound (lb) | kilogram (kg) | kg=0.4536*lb | nearest kg |
| Inflation Pressure | Pounds per square in. (psi) | kilopascal (kPa) | kPa=6.895*psi | nearest kPa |
| Speed | miles per hour (mph) | kilometers per hour (km/h) | km/h=1.609*mph | nearest km/h |
| Torque | inch-pound (in-lb) | Newton.meter (N.m) | N.m=.113*in-lb | nearest N.m |

---

*. Applicable in tire dimensions.

## Table A.4

Index of Agricultural Section

(The Tire and Rim Association Inc., Yearbook 1984)

| Vehicles | Tire Type |
|---|---|
| 1. Agricultural Tractors Used in Field Service | 1.1. Steering Wheel<br>1.2. Diagonal (Bias) Ply Drive Wheels<br>1.2.1. Singles<br>1.2.2. Duals<br>1.3. Radial Ply Drive Wheels (Singles and Duals) |
| 2. Agricultural Implements | All |
| 3. Log-Skidders | All |

## Table A.5

### Tire Coding Nomenclature

(The Tire and Rim Association Inc., Yearbook 1984)

| Code Number | Tire Type |
|---|---|
| F-1 | Agricultural Single Rib Tread |
| F-2 | Agricultural Dual or Triple Rib Tread |
| F-3 | Industrial Multiple Rib Tread |
| R-1 | Drive Wheel Regular Tread |
| R-2 | Cane and Rice Drive Wheel, Deep Tread |
| R-3 | Drive Wheel, Shallow Tread |
| R-4 | Industrial Tractor, Drive Wheel, Intermediate Tread |
| I-1 | Rib Tread |
| I-2 | Moderate Traction |
| I-3 | Traction Tread |
| I-4 | Plow Tail Wheels |
| I-6 | Smooth Tread |

F: Front tires

R: Drive wheel, usually rear tires

I: Implement tires

## Table A.6

Unified Soil Classification System (USCS)

(Holtz and Kovacs, 1981)

| Major Divisions | | | Group Symbols | Typical Names |
|---|---|---|---|---|
| Coarse Grained Soils<br>More than 50% larger than 75μm | Gravels<br>More than 50% larger than 4.75μm | Clean Gravels | GW | Well-graded gravels, gravel sand mixtures, little or no fines. |
| | | | GP | Poorly graded gravels, gravel sand mixtures, litle or no fines. |
| | | Gravels with Fines | GM | Silty gravels, gravel sand mixtures. |
| | | | GC | Clayey gravels, gravel-sand-clay mixtures. |
| | Sands<br>More than 50% smaller than 4.75μm | Clean Sands | SW | Well-graded sands, gravelly sands, little or no fines. |
| | | | SP | Poorly-graded sands, gravelly sands, little or no fines. |
| | | Sands with Fines | SM | Silty sands, sand-silt mixtures. |
| | | | SC | Clayey sands, sand-clay mixtures. |
| Fine Grained Soils<br>More than 50% smaller than 75μm | Silts and Clays<br>Liquid limit less than 50 | | ML | Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity. |
| | | | CL | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays. |
| | | | OL | Organic silts and organic silty clays of low plasticity. |
| | Silts and Clays<br>Liquid limit greater than 50 | | MH | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts. |
| | | | CH | Inorganic clays of high plasticity, fat clays. |
| | | | OH | Organic clays of medium to high plasticity, organic silts. |

# APPENDIX B

# NOMENCLATURE AND PROGRAM INFORMATION

## Table B.1

### IBM PC Hardware Design

| | |
|---|---|
| System Unit: | stand-alone, tabletop unit, containing the power supply, the speaker, the disk drive(s) and the system board. |
| System board: | The Intel 8088 microprocessor.<br>The 8087 Math Coprocessor (optional).<br>ROM in 48 Kbytes of memory.<br>A maximum of 256 K on board RAM.<br>An 8284A Clock Generator.<br>An 8259A Interrupt Controller.<br>An 8255A-5 Programmable Peripheral Interface.<br>An 8253-5 Programmable Interval Timer.<br>An 8237A-5 Direct Memory Access Controller.<br>Supporting Integrated Circuits (IC). |
| Display: | Monochrome Display with Monochrome Display and Printer Adapter or Color Display with Color/ Graphics Monitor Adapter. |
| Keyboard: | The keyboard has 83 keys, arranged in three major groups:<br>left side : 10 programmable function keys;<br>center : 58 keys in a typewriter layout;<br>right side : 15-key keypad. |

## Table B.1 (Cont'd)

Printer: 80 CPS IBM dot matrix printer (optional). The printers are either Matrix Printers or Graphics Printers. Matrix Printers cannot support graphics printout.

Disk drives: One or two $5^1/_4$", single or double sided disk drives.

Note: The above information is an extract of selected topics from the IBM PC Technical Reference and the book of Rector and Alexy (1980) describing the Intel 8086/8088 family of microcomputers.

## Table B.2

HELLAS Integrated Software Subroutine Map

| Address | Title | Comments |
|---|---|---|
| 10 | Initialization | Trapping of errors |
| 300 | Main program | |
| 470 | Main Menu | |
| 620 | Create new file | |
| 840 | Subroutine 1 | Put general information in tirefile |
| 1050 | Subroutine 2 | Find tire size, calculate parameters, put tire info into tractor file |
| 1270 | Tractor analysis | |
| 2190 | General purpose editor | Handling of inputs as strings |
| 1430 | Subroutine 3 | Put parameters into file |
| 1550 | Check database | |
| 1690 | Subroutine 4 | No-File menu |
| 1810 | Subroutine 5 | Entries of No-File Menu |
| 1850 | Subroutine 6 | Display standard format |
| 1910 | Subroutine 7 | FIELD statements |
| 1950 | Subroutine 8 | Reset tractor performance arrays |
| 2260 | Subroutine 9 | Assign standard format fields into variables |
| 2420 | Edit old file | |

## Table B.2 (Cont'd)

| Address | Title | Comments |
|---|---|---|
| 2680 | Edit entry | |
| 2900 | Subroutine 10 | Standard format entries |
| 2950 | Tractor file fields | |
| 3080 | Tire file fields | |
| 3120 | Subroutine 11 - Supervisor | Control flow of file read control offset |
| 3180 | Subroutine 11/A | Tractor general information |
| 3280 | Subroutine 11/B | PUT first set of parameters |
| 3330 | Subroutine 11/C | PUT second set of parameters |
| 3420 | Subroutine 11/D | PUT third set of parameters |
| 3460 | Subroutine 11/E | PUT regression parameters |
| 3500 | Subroutine 11/F | PUT regression parameters |
| 3540 | Subroutine 12 - Supervisor | Control flow of file read |
| 3600 | Subroutine 12/A | Tractor general information |
| 3720 | Subroutine 12/B | GET first set of parameters |
| 3770 | Subroutine 12/C | GET second set of parameters |
| 3800 | Subroutine 12/D | GET third set of parameters |
| 3830 | Subroutine 12/E | GET regression parameters |
| 3860 | Subroutine 13 - Supervisor | Control flow of write screen |
| 3970 | Subroutine 13/A | Write page zero |
| 4040 | Subroutine 13/B | Write page one |
| 4070 | Subroutine 13/C | Write page two |
| 4100 | Subroutine 13/D | Write page three |

Table B.2 (Cont'd)

| Address | Title | Comments |
|---|---|---|
| 4160 | Printout file | |
| 4390 | Subroutine 14/A | Print tractor information |
| 4460 | Subroutine 14/B | Print tractor performance information |
| 4660 | Simulation routine | |
| 4760 | Select model, soil & implement | |
| 4940 | Model 1 | ASAE D230.4 |
| 5390 | Model 2 | OECD |
| 5640 | Model 3 | HELLAS |
| 5890 | Rolling Resistance coefficient | |
| 6010 | Release simulation output | |
| 6130 | Update directory | |
| 6240 | General purpose editor | |
| 6360 | Option selection menu | |
| 6650 | Communication package (not implemented) | |
| 6680 | Statistical analysis | |
| 6830 | Load values | |
| 7070 | Simple regresion analysis | |
| 7190 | Multiple regression analysis | |
| 7450 | Matrix division | |
| 7500 | Matrix inversion | |
| 7700 | Subroutine 14 | Calculate predicted values |
| 7820 | Graphics | |
| 8000 | Color graphics / High resolution | |
| 8030 | Axes labels | |
| -- | | |

Table B.2 (Cont'd)

| Address | Title | Comments |
|---|---|---|
| 8070 | Monochrome graphics / ASCII | |
| 8210 | Service routines - Group 2 | |
| 9630 | Utilities | |
| 9820 | Tractor library utility | |
| 10340 | Tire library utility | |
| 11120 | File manager | |
| 11450 | Check filename syntax | |
| 11510 | Error handling | |

## Table B.3

Standard Format for Tractor Design Parameters

| Field | Type of parameter |
|---|---|
| Job number | integer |
| Number of observations | integer |
| Tractor full name | alphanumeric |
| Rated engine power | real |
| Test location | alphanumeric |
| Test number | alphanumeric |
| Date(s) of test | alphanumeric |
| Test track surface | alphanumeric |
| Front (Inner) tire size | alphanumeric |
| Front (Inner) tire ply rating | integer |
| Front (Inner) tire pressure | integer |
| Number of front (Inner) tires | integer |
| Rear (Outer) tire size | alphanumeric |
| Rear (Outer) tire ply rating | integer |
| Rear (Outer) tire pressure | integer |
| Number of rear (Outer) tires | integer |
| Front static weight | real |
| Total tractor weight | real |
| Drawbar height | real |
| Wheelbase | real |
| Rated engine RPM | integer |

## Table B.4

Display Tractor File Information.

Page one: includes the basic menu of tractor design specifications plus information about:

- rear static weight
- front tire rolling radius
- rear tire rolling radius
- total rolling resistance coefficient
- distance of center of gravity from rear axle
- front tire loading
- rear tire loading

Page two:

- gear setting
- engine RPM
- Thrust
- tire effective arm
- Drawbar Power
- PTO Power
- Axle input Power
- Drawbar Pull

Table B.4 (Cont'd)

| | |
|---|---|
| Page three: | - gear setting |
| | - ground speed |
| | - theoretical speed |
| | - slip |
| | - travel ratio |
| | - dynamic front weight (axle) |
| | - dynamic rear weight (axle) |
| | - calculated weight transfer |
| Page four: | - gear setting |
| | - axle input torque |
| | - Dynamic Traction Ratio (DTR) |
| | - Gross Traction Ratio (GTR) |
| | - Force Efficiency |
| | - Power coefficient |
| | - Tractive Efficiency |
| | - total motion resistance |

## Table B.5

List of Variables for Program Equations

DFRONT : Front tire size

DREAR : Rear tire size

IFPLY : Front tire ply rating

IPF : Front tire inflation pressure at rated load

IPR : Rear tire inflation pressure at rated load

IRPLY : Rear tire ply rating

IRPM : Engine speed

LDF : Front tire rated load

LDR : Rear tire rated load

NGR : Gear selection

NUMF : Number of front tires

NUMR : Number of rear tires

PF : Front tire inflation pressure

PLDF : Percent loading of front tires

PLDR : Percent loading of rear tires

PR : Rear tire inflation pressure

PRMTR : Parameter (ct)

PTOPWR : PTO Power

PULL : Drawbar Pull

PWREFF : Power coefficient

RRCF : Motion resistance coefficient of front tires

RRCR : Motion resistance coefficient of rear tires

RRTOTL : Tractor total motion resistance

SFWT : Static front weight

## Table B.5 (Cont'd)

SLIP : Wheel slip or travel reduction

SRWT : Static rear weight

STOWT : Total tractor weight

TAXPWR : Axle input power

TCGDST : Tractor static center of gravity

TCWTR : Tractor calculated weight transfer

TDBH : Tractor drawbar height

TDBPWR : Drawbar Power

TDF : Front tire overall diameter

TDFWT : Tractor dynamic front weight

TDR : Rear tire overall diameter

TDRWT : Tractor dynamic rear weight

TDTR : Dynamic Traction or Pull Ratio

TEA : Tire effective arm (rolling radius)

TFCEFF : Force Efficiency

TGTR : Gross Traction or Torque Ratio

THRUST : Gross Thrust

TORQUE : Axle (wheel) input Torque

TREFF : Tractive Efficiency

TRF : Front tire loaded radius

TRR : Rear tire loaded radius

TRRT : Travel Ratio

V : Theoretical (zero-slip) tractor velocity

VA : Actual (ground) tractor velocity

WHLBS : Tractor wheelbase

## Table B.6

### Equations for the ASAE D230.4 Prediction Model

Legend:

Soil : Firm (F), Tilled (T), Soft (S)

Implement : Integral (II), Semi-mounted (SI), Towed (TI)

Quadrant 1

$Y_{400} = -0.02010 + X*0.1111$

$Y_{500} = -0.01700 + X*0.1381$

$Y_{600} = -0.01660 + X*0.1645$

$Y_{700} = -0.00150 + X*0.1897$

$Y_{800} = -0.02520 + X*0.2192$

$Y_{900} = -0.02617 + X*0.2467$

$Y_{1000} = -0.01600 + X*0.2737$

$Y_{1100} = -0.04000 + X*0.3030$

$Y_{1200} = -0.05840 + X*0.3300$

$Y_{1300} = -0.03170 + X*0.3515$

$Y_{1400} = -0.04920 + X*0.3803$

$Y_{1600} = -0.06180 + X*0.4356$

$Y_{2000} = -0.03100 + X*0.5165$

$Y_{2400} = -0.14410 + X*0.6346$

## Table B.6 (Cont'd)

Quadrant2

F/II: $Y=1/(-0.0273+0.07707*X)$

F/SI: $Y=25.17217*X^{-1.5084}$

F/TI: $Y=1/(-0.06178+0.08248*X)$

T/II: $Y=27.767*X^{-1.6026}$

T/SI: $Y=1/(-0.06178+0.08248*X)$

T/TI: $Y=44.84557*X^{-1.92993}$

S/II: $Y=117.3558 - X*86.79160 + X^2*23.3799 - X^3*2.1465$

S/SI: $Y=120.4186 - X*84.21870 + X^2*21.3694 - X^3*1.8515$

S/TI: $Y=134.5241 - X*93.02687 + X^2*23.1864 - X^3*1.9700$

Quadrant 3

Pull Ratio

F/II: $Y=-0.03845 + X*0.06798 - X^2*0.001290 + X^3*9.20E-06$

F/SI: $Y=-0.02850 + X*0.06730 - X^2*0.001940 + X^3*0.000024$

F/TI: $Y=-0.02690 + X*0.05979 - X^2*0.001700 + X^3*1.90E-05$

T/II: $Y=-0.02613 + X*0.05170 - X^2*0.001297 + X^3*0.000015$

T/SI: $Y=-0.02124 + X*0.04820 - X^2*0.001275 + X^3*0.000014$

T/TI: $Y=-0.02260 + X*0.04590 - X^2*0.001360 + X^3*0.000017$

S/II: $Y=-0.07320 + X*0.03827 - X^2*0.001240 + X^3*0.000015$

S/SI: $Y=-0.06950 + X*0.03496 - X^2*0.001100 + X^3*0.000013$

S/TI: $Y=-0.07150 + X*0.03277 - X^2*0.001000 + X^3*1.14E-05$

Tractive Efficiency

F/ : $Y=0.39930 + X*0.08280 - X^2*0.00520 + X^3*0.0000900$

T/ : $Y=0.28685 + X*0.06498 - X^2*0.00356 + X^3*0.0000055$

S/ : $Y=0.20415 + X*0.05000 - X^2*0.00230 + X^3*.00002900$

## Table B.7

## Equations Involved in the Calculation of the Motion Resistance Coefficient

(Inns and Kilgour, 1974)

Concrete:

$Y=0.08510 - 1.06E-04*X + 5.24E-08*X^2$

Pasture:

$Y=0.09580 - 9.10E-05*X + 4.50E-08*X^2$

Cultivated and settled loam:

$Y=0.23327 - 1.30E-04*X + 2.40E-09*X^2$

Freshly cultivated loam:

$Y=0.59835 - 7.65E-04*X + 2.00E-07*X^2 - 1.00E-10*X^3$

Correction of motion resistance coefficient for tire inflation pressure compared to 100 kPa:

$Y_{70} = 0.005770 + 0.87526*X$

$Y_{100} = 0.000288 + 1.02078*X$

$Y_{150} = -0.008700 + 1.21117*X$

$Y_{200} = -0.015230 + 1.43489*X$

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | CTNO $ | IDERR % | UNIT% % | MODEL % | LAND % | IMPL % | VCNIX ! | LAB % |
| 2 | NOBS % | DESIGN $ | ALOC $ | APL $ | JOBN % | DATE $ | FSURF $ | |
| 3 | DFRONT $ | NUMF % | IFPLY % | PF ! | DREAR $ | NUMR % | IRPLY % | PR ! |
| 4 | RATPWR ! | SFWT ! | SRWT ! | STOWT ! | OPRPM % | TDBH ! | WHLBS ! | TCGDST ! |
| 5 | TRF ! | TRR ! | RRC ! | PLDF ! | PLDR ! | | | |
| 6 | LDF % | IPF ! | TWF ! | TDF ! | LDR % | IPR % | TWR ! | TDR ! |
| 7 | INGA(1) % | INGA(2) % | INGA(3) % | INGA(4) % | INGA(5) % | INGA(6) % | INGA(7) % | |
| 7 | INGA(8) % | INGA(9) % | INGA(10) % | INGA(11) % | INGA(12) % | INGA(13) % | INGA(14) % | |
| 8 | RGP(41) ! | RGP(42) ! | RGP(43) ! | RGP(44) ! | RGP(45) ! | RGP(46) ! | RGP(47) ! | |
| 8 | RGP(48) ! | RGP(49) ! | RGP(50) ! | RGP(51) ! | RGP(52) ! | RGP(53) ! | RGP(54) ! | |
| | NGR(1) % | TDBPWR(1) ! | PULL(1) ! | SLIP(1) ! | VA(1) ! | IRPM(1) % | | |
| 9 NOBS | | | | | | | | |
| | NGR(N) % | TDBPWR(N) ! | PULL(N) ! | SLIP(N) ! | VA(N) ! | IRPM(N) % | | |
| | PTOPWR(1) ! | TAXPWR(1) ! | TORQUE(1) ! | TCWTR(1) ! | TRRT(1) ! | TDTR(1) ! | TGTR(1) ! | THRUST(1) ! |
| 10 NOBS | | | | | | | | |
| | PTOPWR(N) ! | TAXPWR(N) ! | T[illegible]QUE(N) ! | TCWTR(N) ! | TRRT(N) ! | TDTR(N) ! | TGTR(N) ! | THRUST(N) ! |
| | TREFF(1) ! | PWREFF(1) ! | TR[illegible](1) ! | TDFWT(1) ! | TDRWT(1) ! | RRTOTL(1) ! | V(1) ! | TEA(1) ! |
| 11 NOBS | | | | | | | | |
| | TREFF(N) ! | PWREFF(N) ! | TREFF(N) ! | TDFWT(N) ! | TDRWT(N) ! | RRTOTL(N) ! | V(N) ! | TEA(N) ! |

■▨

■ : VARIABLE NAME

▨ : VARIABLE TYPE

$ :STRING
% :INTEGER
! :SINGLE PRECISION

L#: FIELD FORMAT

L :LETTER
# :NUMBER

Table B.8. Internal Structure of the Database Files

# APPENDIX C

# TRACTOR DATA SHEET AND SAMPLE OUTPUTS

## Abreviations

2WD : Two-Wheel Drive Tractor
FWA : Front Wheel Assist Tractor
4WD : Four-Wheel Drive Tractor
TR : Travel Reduction or Slip
DBPL : Drawbar Pull
PR : Pull or Dynamic Traction Ratio
TE : Tractive Efficiency
$S_1$ : Firm soil
$S_2$ : Tilled soil
$S_3$ : Soft soil
$I_1$ : Integral implement
$I_2$ : Semi-mounted implement
$I_3$ : Towed implement

The models are represented in the histograms as follows:

▨ ASAE D230.4
■ OECD
▒ HELLAS

| | |
|---|---|
| TRACTOR | FORD TW-20 DIESEL |
| TEST LOCATION | NEBRASKA |
| TEST NUMBER | 1300 |
| TEST DATE | 22/03-10/04/79 |
| RELEASE DATE | 03-12-1986 |
| METHOD | NEBRASKA |
| SURFACE | CONCRETE |
| TYPE OF HITCH | TOWED |
| TIRES: FRONT | 11.00X16 : 6 : 220 : 2 |
| REAR | 18.40X38 : 8 : 110 : 4 |
| KW @ 2200 RPM | 101.11 |

| SFWT | SRWT | STOWT | RATED RPM | FRR | RRR |
|---|---|---|---|---|---|
| 1651 | 6142 | 7793 | 2200 | 0.447 | 0.782 |

| DBH | WHLBS | CGDIST | PLDF (%) | PLDR (%) | MT RES CF |
|---|---|---|---|---|---|
| 0.535 | 2.785 | 0.590 | 72.424 | 70.744 | 0.064 |

| GR | ENG RPM | TR EF ARM | THRUST | DB POWER | PTO POWER | AXLE POWER | PULL |
|---|---|---|---|---|---|---|---|
| 3 | 2392 | 0.610 | 65.411 | 70.100 | 89.226 | 85.657 | 62.970 |
| 4 | 2201 | 0.610 | 64.951 | 83.990 | 102.676 | 98.569 | 62.510 |
| 5 | 2200 | 0.611 | 63.431 | 84.740 | 102.136 | 98.050 | 60.990 |
| 6 | 2200 | 0.620 | 50.041 | 86.710 | 101.588 | 97.525 | 47.600 |
| 7 | 2200 | 0.620 | 49.551 | 89.190 | 104.581 | 100.397 | 47.110 |
| 8 | 2202 | 0.625 | 42.471 | 88.970 | 103.585 | 99.442 | 40.030 |
| 9 | 2199 | 0.627 | 38.091 | 88.440 | 103.213 | 99.085 | 35.650 |
| 10 | 2198 | 0.630 | 33.721 | 90.500 | 105.764 | 101.534 | 31.280 |
| 11 | 2200 | 0.634 | 28.261 | 90.580 | 106.663 | 102.396 | 25.820 |
| 12 | 2198 | 0.638 | 22.352 | 88.540 | 105.981 | 101.742 | 19.910 |

| GR | GND SPEED | TH SPEED | SLIP | TRV RAT | DFWT | DRWT | CALWTR |
|---|---|---|---|---|---|---|---|
| 3 | 4.010 | 4.714 | 14.940 | 0.851 | 363.261 | 7429.739 | 1287.739 |
| 4 | 4.840 | 5.463 | 11.410 | 0.886 | 372.242 | 7420.758 | 1278.758 |
| 5 | 5.000 | 5.565 | 10.150 | 0.899 | 401.919 | 7391.081 | 1249.081 |
| 6 | 6.560 | 7.016 | 6.500 | 0.935 | 663.350 | 7129.650 | 987.650 |
| 7 | 6.820 | 7.294 | 6.500 | 0.935 | 672.917 | 7120.084 | 978.084 |
| 8 | 8.000 | 8.429 | 5.090 | 0.949 | 811.148 | 6981.852 | 839.851 |
| 9 | 8.930 | 9.365 | 4.640 | 0.954 | 896.665 | 6896.335 | 754.335 |
| 10 | 10.420 | 10.839 | 3.870 | 0.961 | 981.986 | 6811.014 | 669.014 |
| 11 | 12.630 | 13.043 | 3.170 | 0.968 | 1088.589 | 6704.411 | 562.411 |
| 12 | 16.010 | 16.387 | 2.300 | 0.977 | 1203.978 | 6589.023 | 447.022 |

| GR | TORQUE | DTR | GTR | FRC EFF | PWR COEFF | TREFFY | RRTOTL |
|---|---|---|---|---|---|---|---|
| 3 | 39.900 | 0.864 | 0.897 | 0.963 | 0.735 | 0.818 | 2.441 |
| 4 | 39.639 | 0.859 | 0.892 | 0.962 | 0.761 | 0.852 | 2.441 |
| 5 | 38.773 | 0.841 | 0.875 | 0.962 | 0.756 | 0.864 | 2.441 |
| 6 | 31.017 | 0.681 | 0.715 | 0.951 | 0.636 | 0.889 | 2.441 |
| 7 | 30.729 | 0.674 | 0.709 | 0.951 | 0.631 | 0.888 | 2.441 |
| 8 | 26.530 | 0.584 | 0.620 | 0.943 | 0.555 | 0.895 | 2.441 |
| 9 | 23.901 | 0.527 | 0.563 | 0.936 | 0.503 | 0.893 | 2.441 |
| 10 | 21.253 | 0.468 | 0.505 | 0.928 | 0.450 | 0.891 | 2.441 |
| 11 | 17.911 | 0.393 | 0.430 | 0.914 | 0.380 | 0.885 | 2.441 |
| 12 | 14.250 | 0.308 | 0.346 | 0.891 | 0.301 | 0.870 | 2.442 |

Table C.1. Data Sheet for the FORD TW-20 2WD Tractor.

| | |
|---|---|
| TRACTOR | KUBOTA M5500 DT |
| TEST LOCATION | NEBRASKA |
| TEST NUMBER | 1369 |
| TEST DATE | 04/10-16/10/1980 |
| RELEASE DATE | 03-12-1986 |
| METHOD | NEBRASKA |
| SURFACE | CONCRETE |
| TYPE OF HITCH | TOWED |
| TIRES: FRONT | 9.50X24 : 6 : 140 : 2 |
| REAR | 16.90X28 : 6 : 125 : 2 |
| KW @ 2400 RPM | 40.26 |

| SFWT | SRWT | STOWT | RATED RPM | FRR | RRR |
|---|---|---|---|---|---|
| 1433 | 2518 | 3951 | 2400 | 0.478 | 0.645 |

| DBH | WHLBS | CGDIST | PLDF (%) | PLDR (%) | MT RES CF |
|---|---|---|---|---|---|
| 0.495 | 2.055 | 0.745 | 112.582 | 68.387 | 0.058 |

| GR | ENG RPM | TR EF ARM | THRUST | DB POWER | PTO POWER | AXLE POWER | PULL |
|---|---|---|---|---|---|---|---|
| 10 | 2469 | 0.603 | 29.066 | 30.910 | 39.343 | 37.769 | 27.970 |
| 11 | 2400 | 0.604 | 27.267 | 32.870 | 40.878 | 39.242 | 26.170 |
| 12 | 2402 | 0.610 | 19.971 | 33.930 | 40.883 | 39.248 | 18.870 |
| 13 | 2400 | 0.613 | 15.323 | 35.020 | 41.968 | 40.289 | 14.220 |
| 14 | 2401 | 0.615 | 12.485 | 34.580 | 41.587 | 39.924 | 11.380 |

| GR | GND SPEED | TH SPEED | SLIP | TRV RAT | DFWT | DRWT | CALWTR |
|---|---|---|---|---|---|---|---|
| 10 | 3.980 | 4.678 | 14.920 | 0.851 | 713.377 | 3237.623 | 719.623 |
| 11 | 4.520 | 5.181 | 12.760 | 0.872 | 757.473 | 3193.527 | 675.527 |
| 12 | 6.470 | 7.075 | 8.550 | 0.915 | 936.304 | 3014.696 | 496.696 |
| 13 | 8.870 | 9.465 | 6.290 | 0.937 | 1050.217 | 2900.783 | 382.783 |
| 14 | 10.940 | 11.512 | 4.970 | 0.950 | 1119.788 | 2831.212 | 313.212 |

| GR | TORQUE | DTR | GTR | FRC EFF | PWR COEFF | TREFFY | RRTOTL |
|---|---|---|---|---|---|---|---|
| 10 | 17.520 | 0.881 | 0.915 | 0.962 | 0.749 | 0.818 | 1.096 |
| 11 | 16.472 | 0.835 | 0.870 | 0.960 | 0.729 | 0.838 | 1.097 |
| 12 | 12.173 | 0.638 | 0.675 | 0.945 | 0.584 | 0.865 | 1.101 |
| 13 | 9.393 | 0.500 | 0.538 | 0.928 | 0.468 | 0.869 | 1.103 |
| 14 | 7.679 | 0.410 | 0.450 | 0.912 | 0.389 | 0.866 | 1.105 |

Table C.2. Data Sheet for the KUBOTA M5500 FWA Tractor.

| | |
|---|---|
| TRACTOR | CASE 4890 DIESEL |
| TEST LOCATION | NEBRASKA |
| TEST NUMBER | 1330 |
| TEST DATE | 22/10-29/10/1979 |
| RELEASE DATE | 03-12-1986 |
| METHOD | NEBRASKA |
| SURFACE | CONCRETE |
| TYPE OF HITCH | TOWED |
| TIRES: INNER | 20.80X34 : 8 : 110 : 4 |
| OUTER | 20.80X34 : 8 : 110 : 4 |
| KW @ 2200 RPM | 188.97 |

| SFWT | SRWT | STOWT | RATED RPM | FRR | RRR |
|---|---|---|---|---|---|
| 5280 | 7630 | 12910 | 2200 | 0.800 | 0.800 |

| DBH | WHLBS | CGDIST | PLDF (%) | PLDR (%) | MT RES CF |
|---|---|---|---|---|---|
| 0.455 | 2.794 | 1.143 | 51.247 | 74.056 | 0.115 |

| GR | ENG RPM | TR EF ARM | THRUST | DB POWER | PTO POWER | AXLE POWER | PULL |
|---|---|---|---|---|---|---|---|
| 2 | 2299 | 0.682 | 129.760 | 141.660 | 183.034 | 87.856 | 122.890 |
| 3 | 2199 | 0.682 | 126.087 | 150.860 | 191.378 | 91.862 | 119.210 |
| 4 | 2199 | 0.682 | 114.272 | 159.120 | 193.158 | 92.716 | 107.370 |
| 5 | 2200 | 0.682 | 98.045 | 166.020 | 198.279 | 95.174 | 91.110 |
| 6 | 2200 | 0.682 | 91.549 | 165.890 | 198.008 | 95.044 | 84.600 |
| 7 | 2200 | 0.682 | 78.736 | 166.450 | 199.154 | 95.594 | 71.760 |
| 8 | 2201 | 0.682 | 69.904 | 167.640 | 201.616 | 96.776 | 62.910 |
| 9 | 2200 | 0.682 | 56.701 | 166.940 | 204.344 | 98.085 | 49.680 |

| GR | GND SPEED | TH SPEED | SLIP | TRV RAT | DFWT | DRWT | CALWTR |
|---|---|---|---|---|---|---|---|
| 2 | 4.150 | 4.875 | 14.870 | 0.851 | 3059.816 | 9850.184 | 2220.184 |
| 3 | 4.560 | 5.246 | 13.070 | 0.869 | 3120.549 | 9789.451 | 2159.451 |
| 4 | 5.340 | 5.842 | 8.590 | 0.914 | 3315.948 | 9594.052 | 1964.051 |
| 5 | 6.560 | 6.989 | 6.140 | 0.939 | 3584.293 | 9325.707 | 1695.707 |
| 6 | 7.060 | 7.475 | 5.550 | 0.944 | 3691.731 | 9218.270 | 1588.270 |
| 7 | 8.350 | 8.742 | 4.480 | 0.955 | 3903.634 | 9006.366 | 1376.367 |
| 8 | 9.590 | 9.968 | 3.790 | 0.962 | 4049.689 | 8860.312 | 1230.312 |
| 9 | 12.100 | 12.455 | 2.850 | 0.971 | 4268.028 | 8641.972 | 1011.972 |

| GR | TORQUE | DTR | STR | FRC EFF | PWR COEFF | TREFFY | RRTOTL |
|---|---|---|---|---|---|---|---|
| 2 | 44.216 | 0.970 | 1.025 | 0.947 | 0.826 | 0.806 | 6.870 |
| 3 | 42.965 | 0.941 | 0.996 | 0.945 | 0.818 | 0.821 | 6.877 |
| 4 | 38.939 | 0.848 | 0.902 | 0.940 | 0.775 | 0.858 | 6.902 |
| 5 | 33.410 | 0.719 | 0.774 | 0.929 | 0.675 | 0.872 | 6.935 |
| 6 | 31.196 | 0.668 | 0.723 | 0.924 | 0.631 | 0.873 | 6.949 |
| 7 | 26.830 | 0.567 | 0.622 | 0.911 | 0.541 | 0.871 | 6.976 |
| 8 | 23.820 | 0.497 | 0.552 | 0.900 | 0.478 | 0.866 | 6.994 |
| 9 | 19.321 | 0.392 | 0.448 | 0.876 | 0.381 | 0.851 | 7.021 |

Table C.3. Data Sheet for the CASE 4890 4WD Tractor.

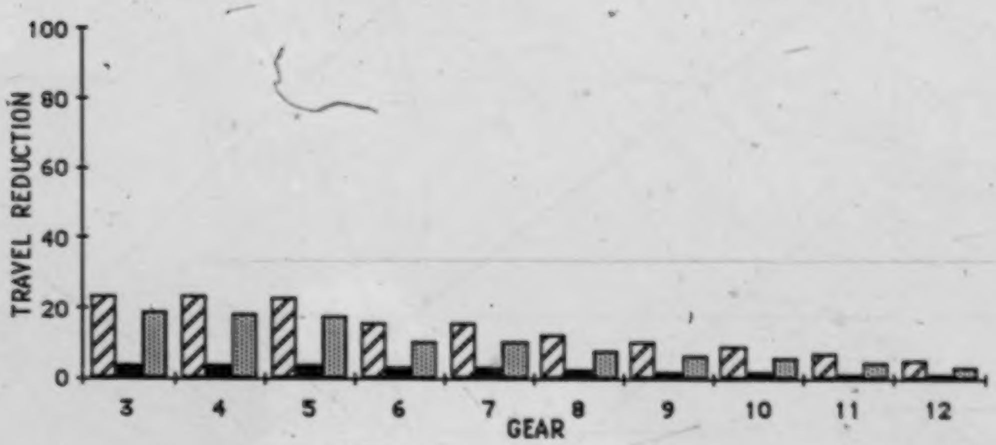


Figure C.1. 2WD/TR/$S_1$/$I_1$

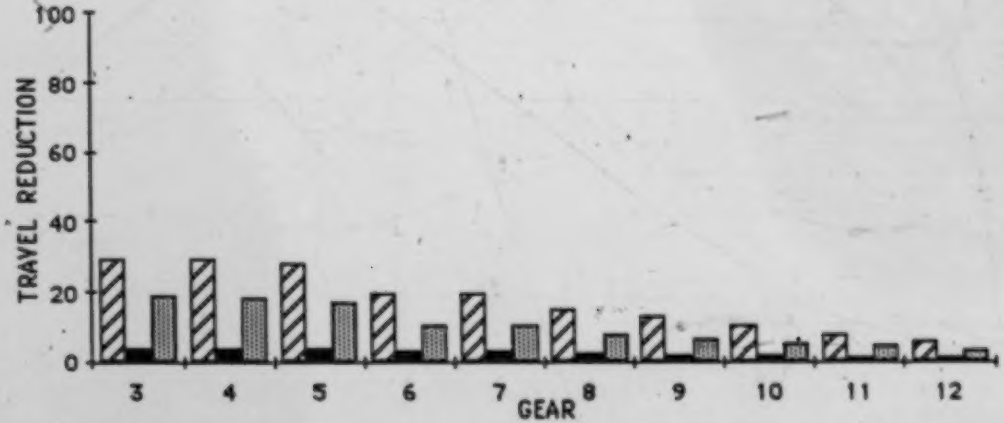


Figure C.2. 2WD/TR/$S_1$/$I_2$

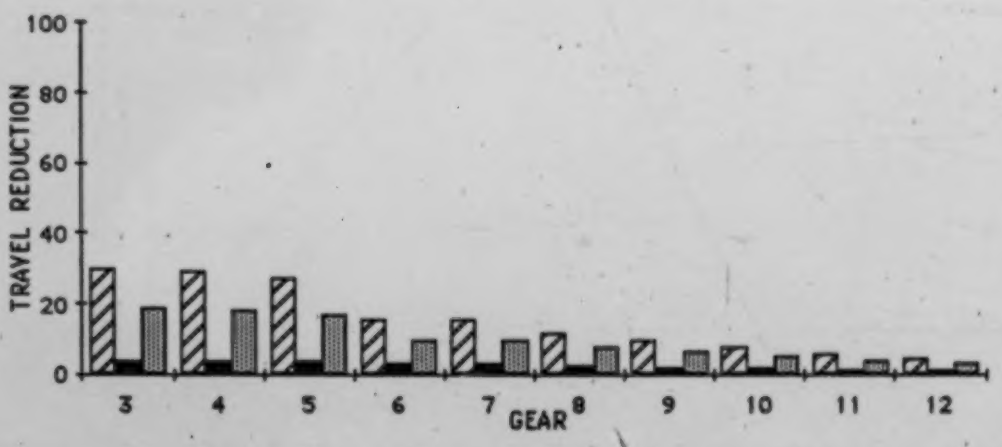


Figure C.3. 2WD/TR/$S_1$/$I_3$

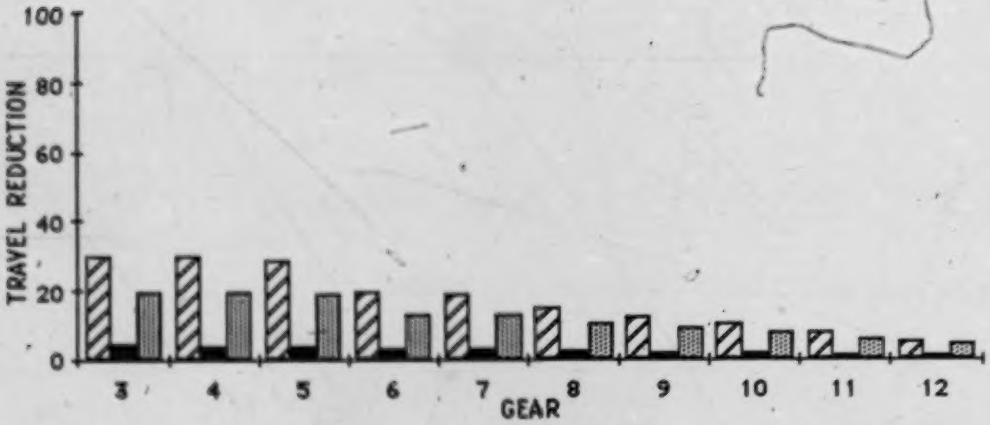


Figure C.4. 2WD/TR/$S_2$/$I_1$

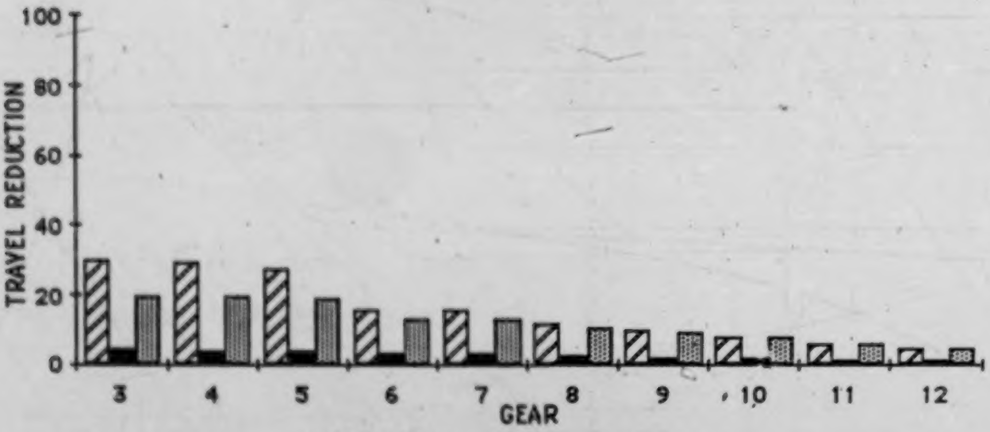


Figure C.5. 2WD/TR/$S_2$/$I_2$

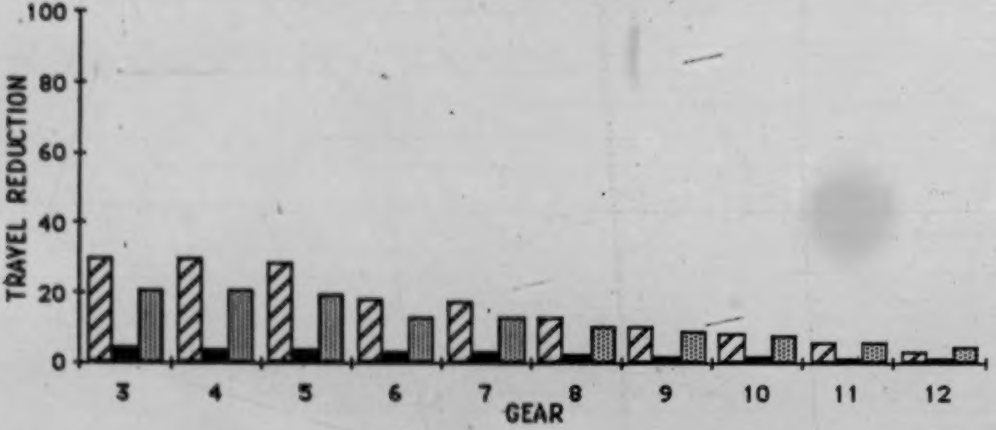


Figure C.6. 2WD/TR/$S_2$/$I_3$

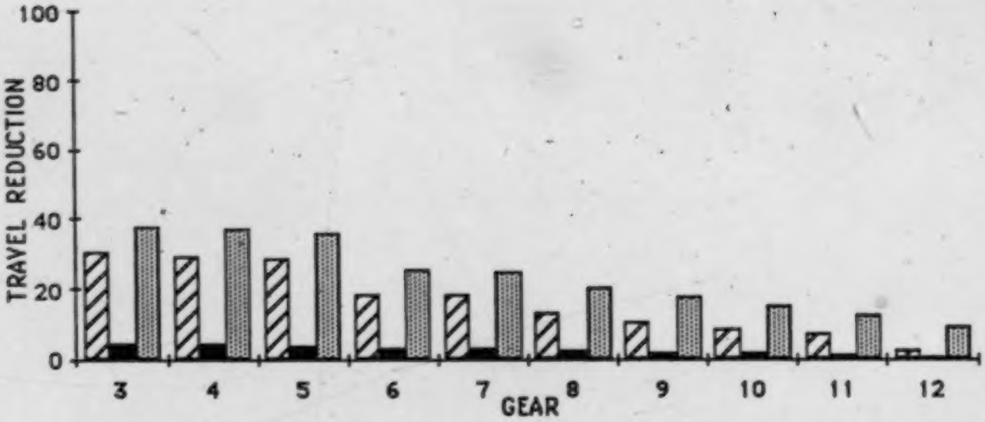


Figure C.7. 2WD/TR/$S_3$/$I_1$

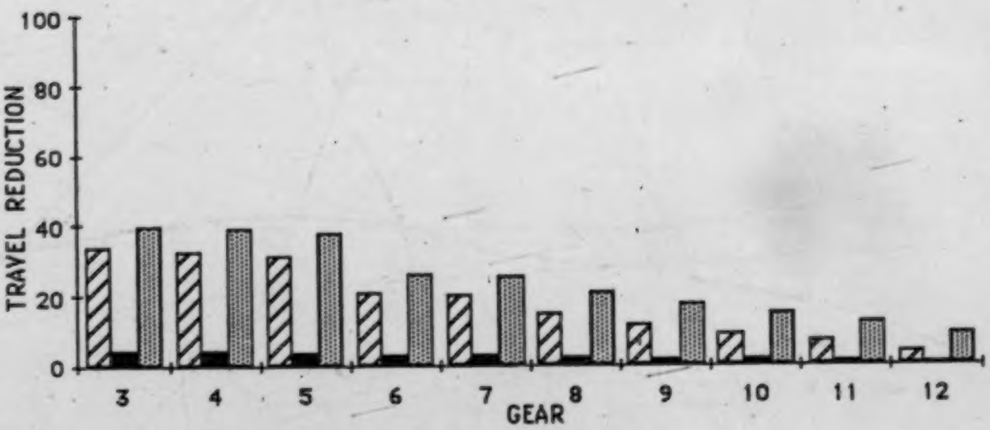


Figure C.8. 2WD/TR/$S_3$/$I_2$

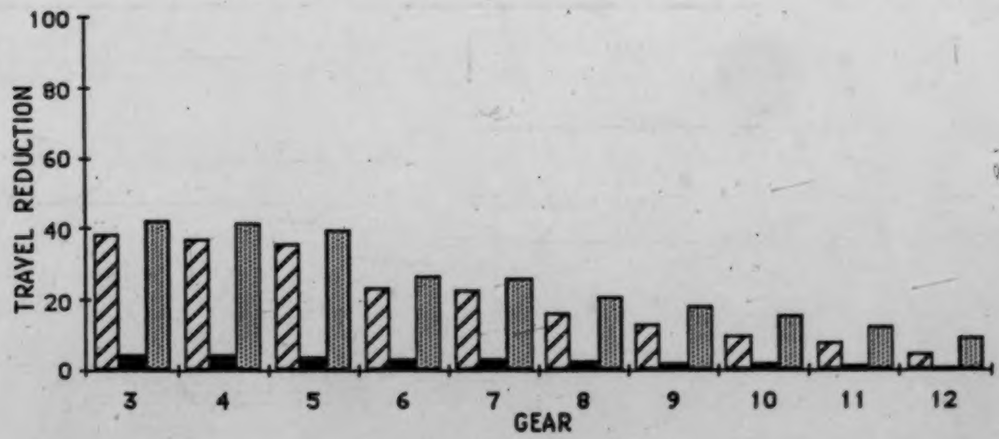


Figure C.9. 2WD/TR/$S_3$/$I_3$

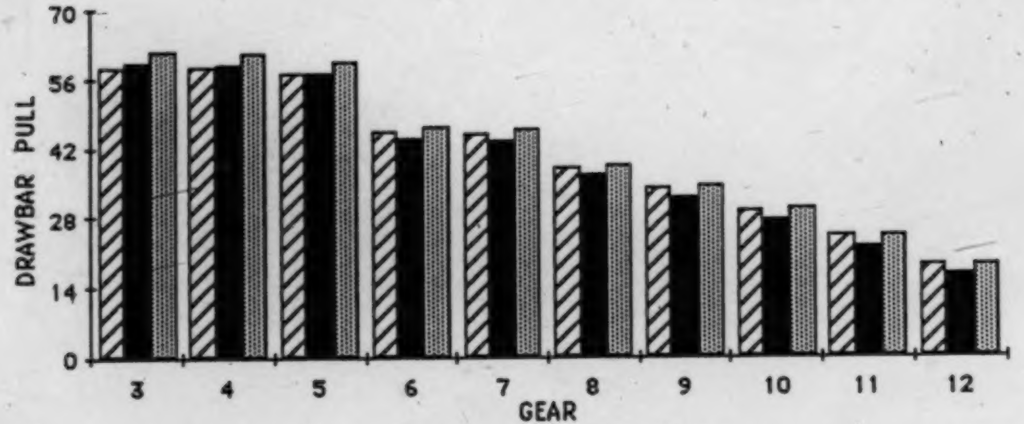


Figure C.10. 2WD/DBPL/$S_1$/$I_1$

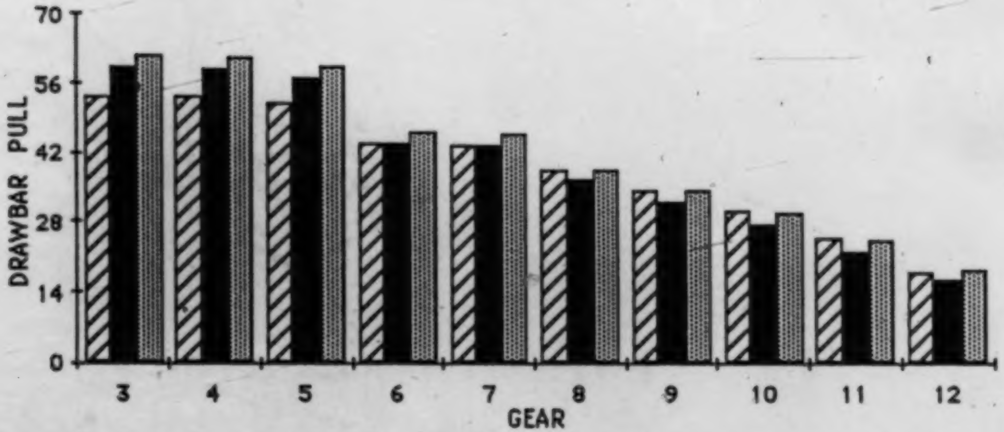


Figure C.11. 2WD/DBPL/$S_1$/$I_2$

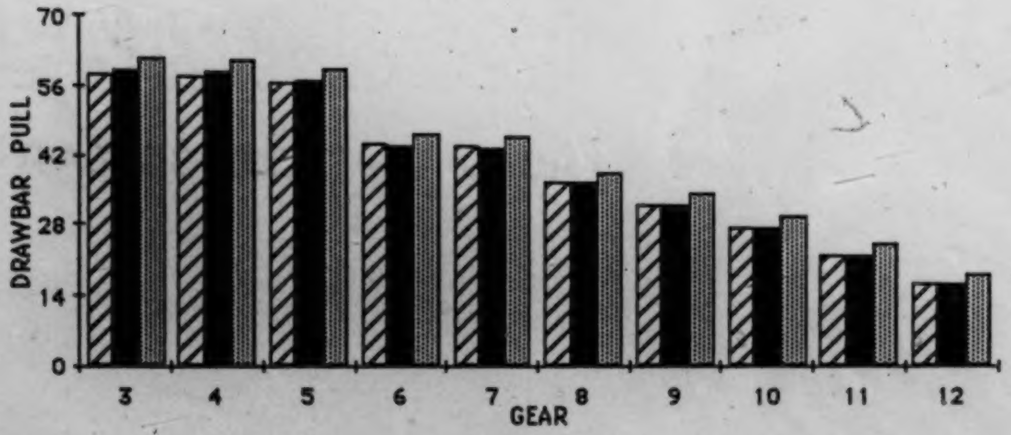


Figure C.12. 2WD/DBPL/$S_1$/$I_3$

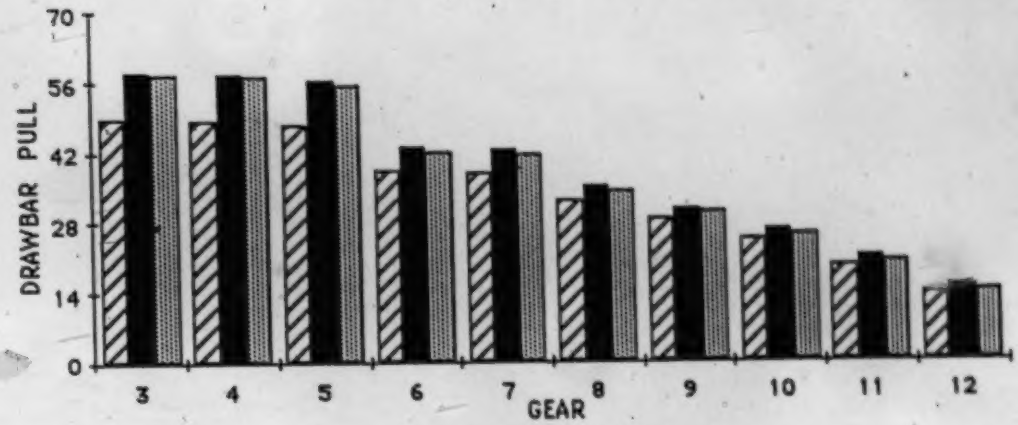


Figure C.13. 2WD/DBPL/$S_2$/$I_1$

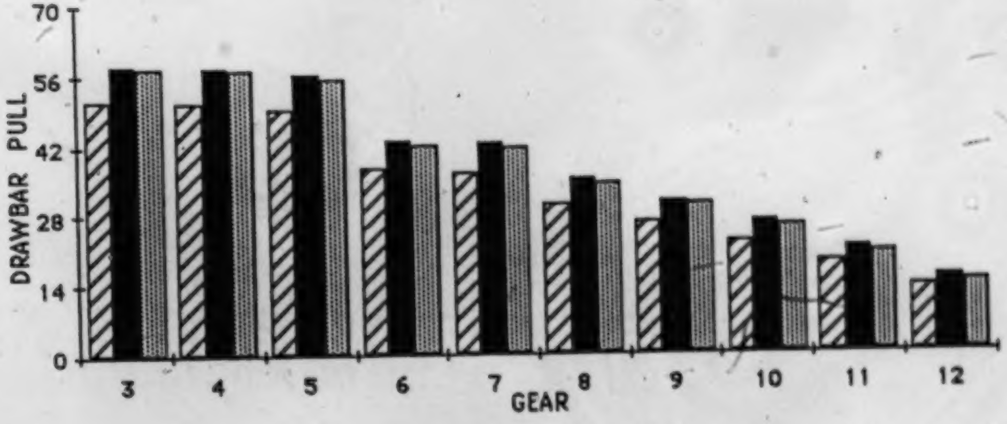


Figure C.14. 2WD/DBPL/$S_2$/$I_2$

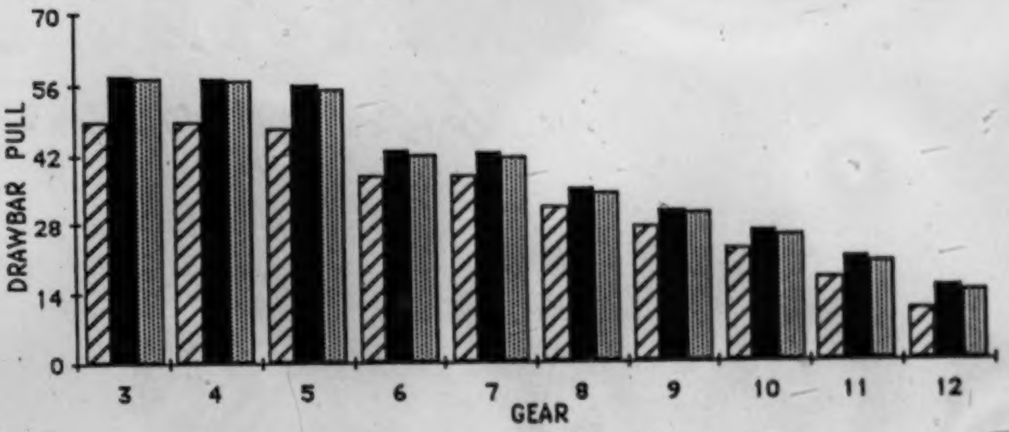


Figure C.15. 2WD/DBPL/$S_2$/$I_3$

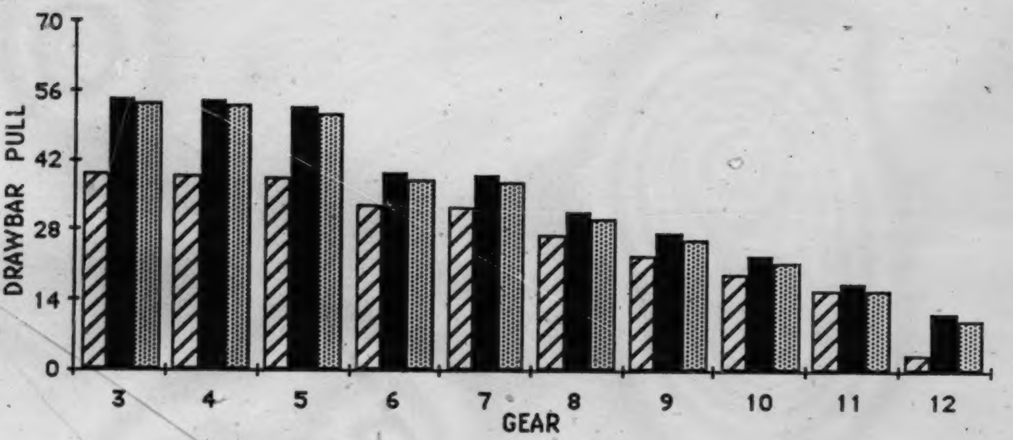


Figure C.16. 2WD/DBPL/$S_3$/$I_1$

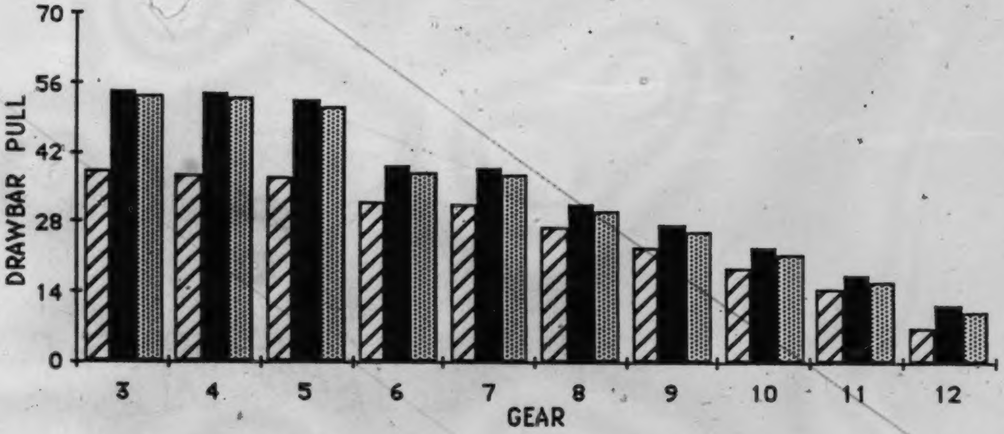


Figure C.17. 2WD/DBPL/$S_3$/$I_2$

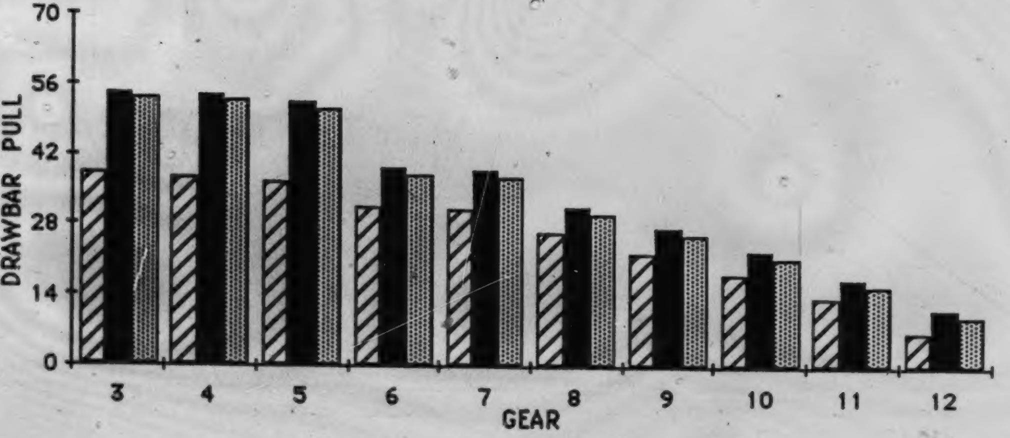


Figure C.18. 2WD/DBPL/$S_3$/$I_3$

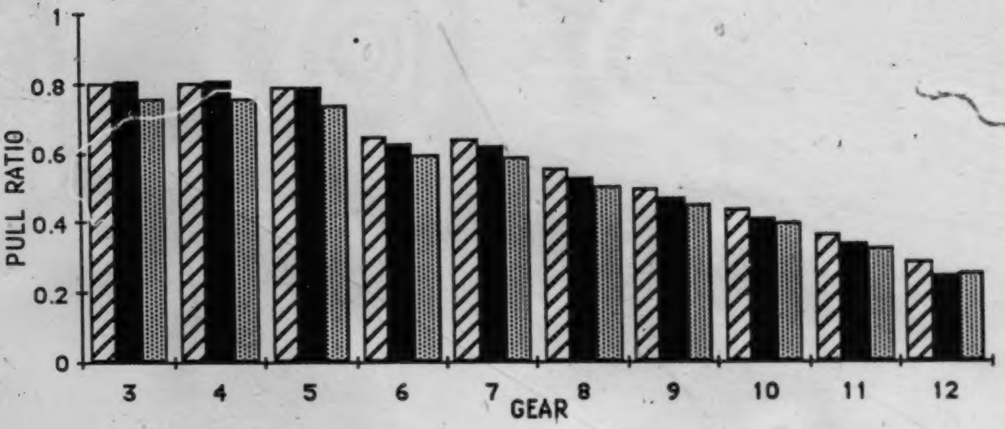


Figure C.19. 2WD/PR/$S_1$/$I_1$

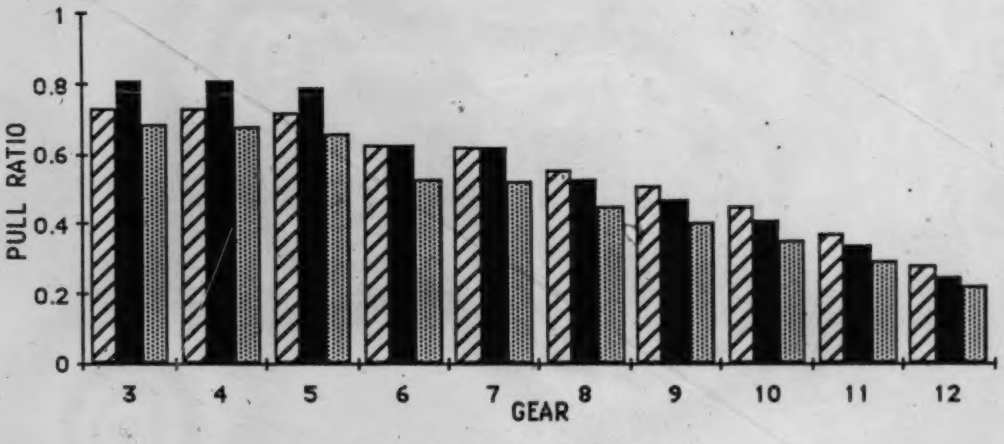


Figure C.20. 2WD/PR/$S_1$/$I_2$

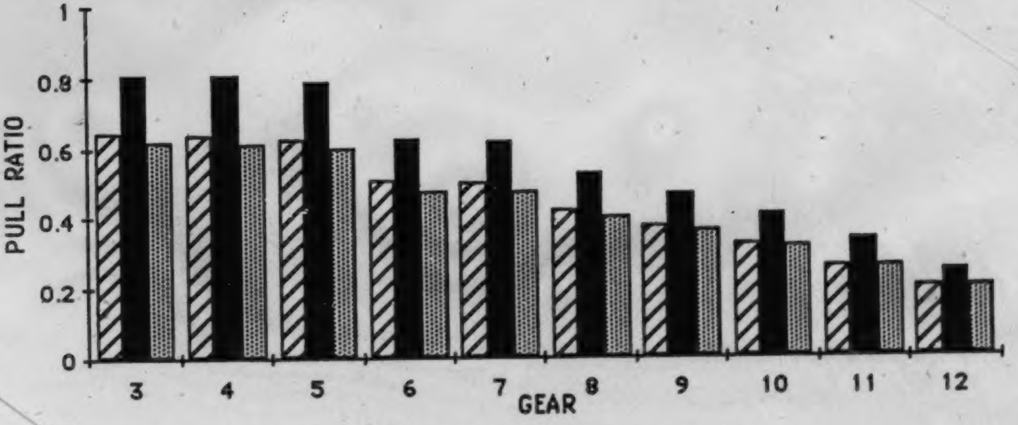


Figure C.21. 2WD/PR/$S_1$/$I_3$

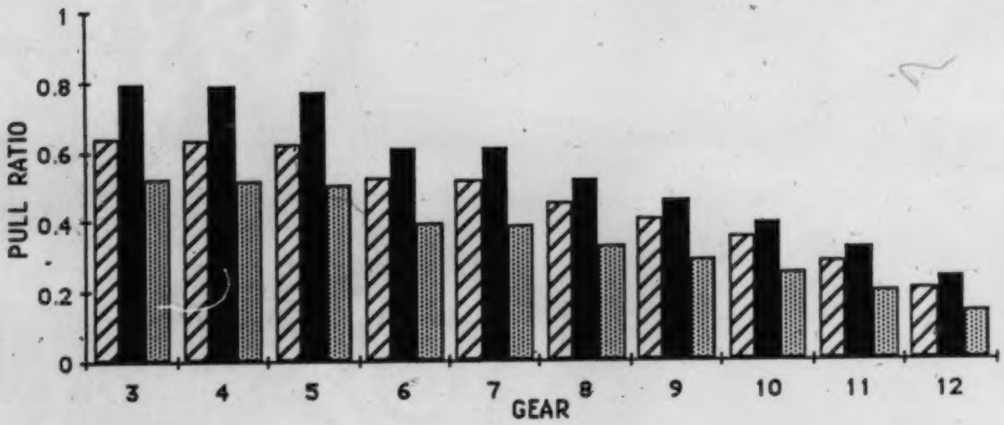


Figure C.22. 2WD/PR/$S_2$/$I_1$

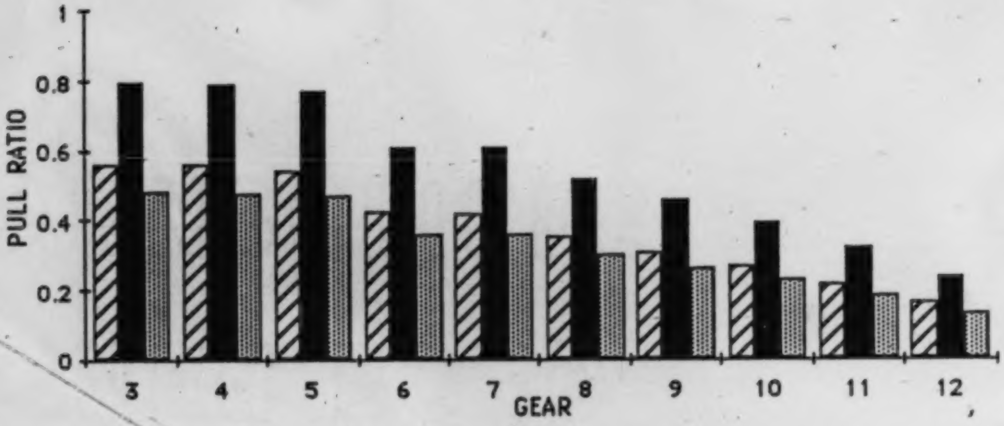


Figure C.23. 2WD/PR/$S_2$/$I_2$

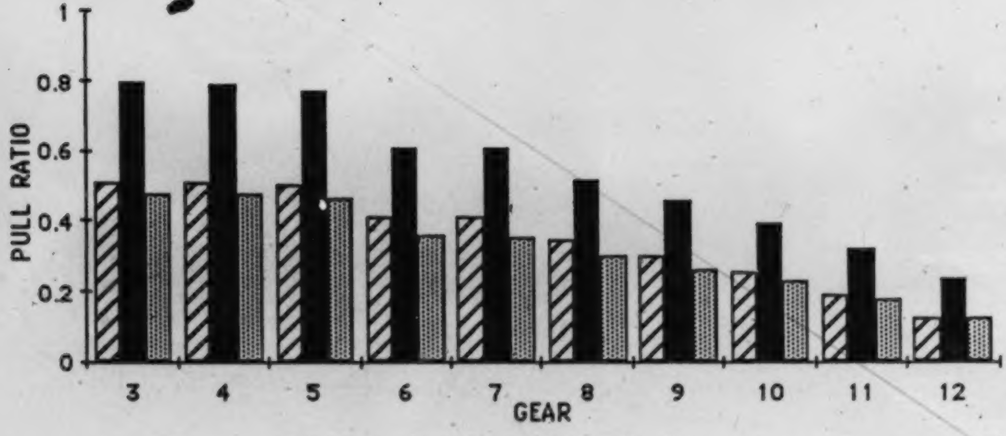


Figure C.24. 2WD/PR/$S_2$/$I_3$

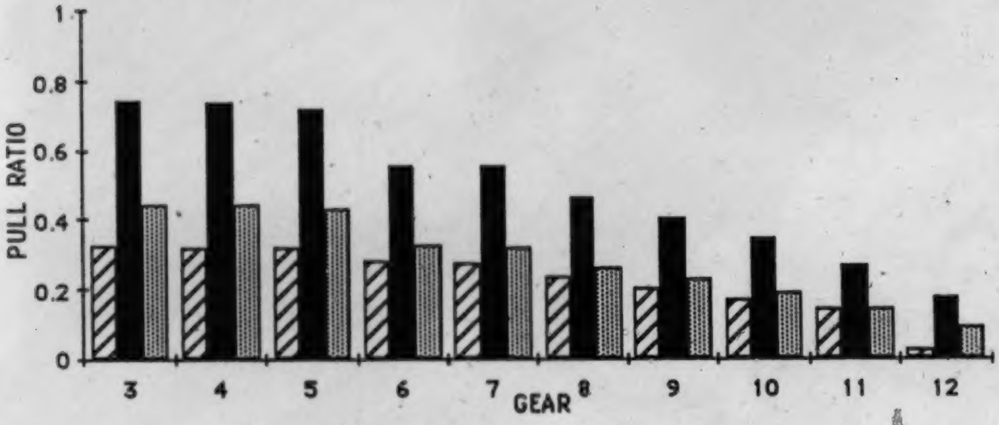


Figure C.25. 2WD/PR/$S_3$/$I_1$

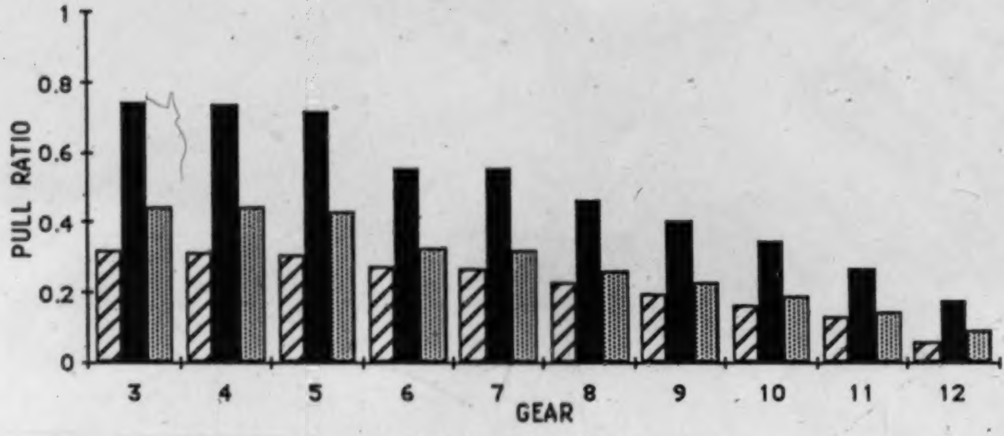


Figure C.26. 2WD/PR/$S_3$/$I_2$

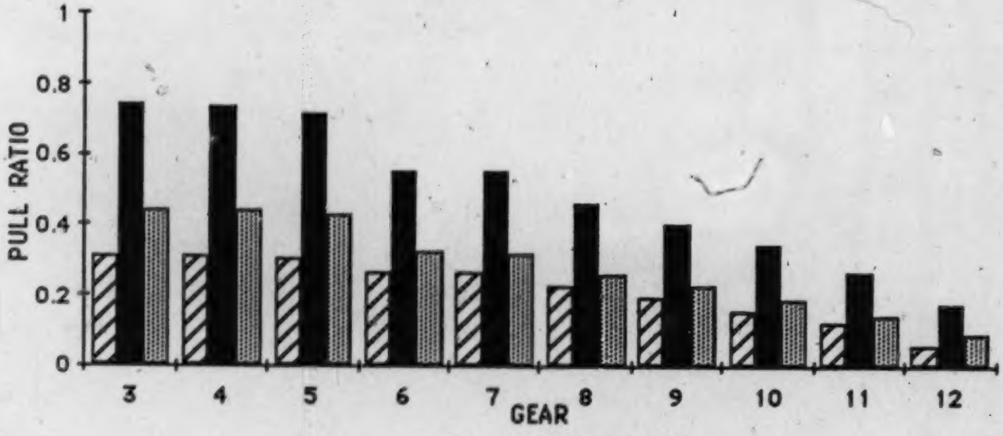


Figure C.27. 2WD/PR/$S_3$/$I_3$

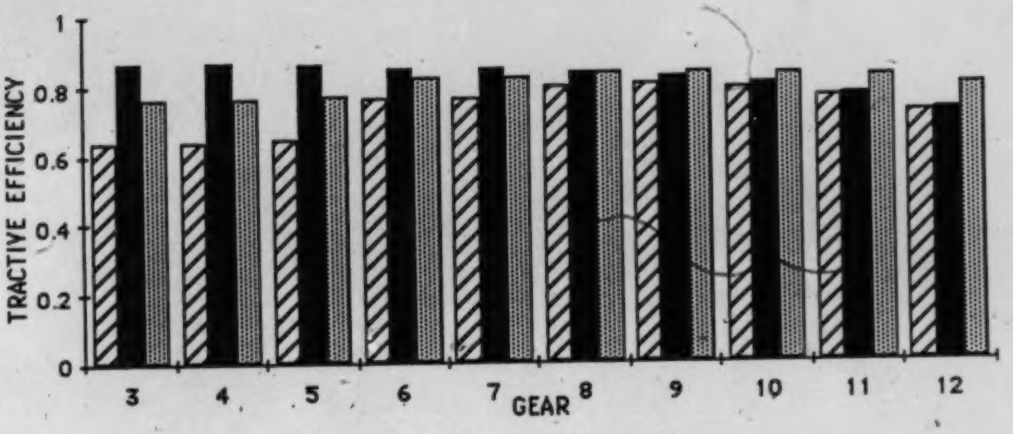


Figure C.28. 2WD/TE/$S_1$/$I_1$

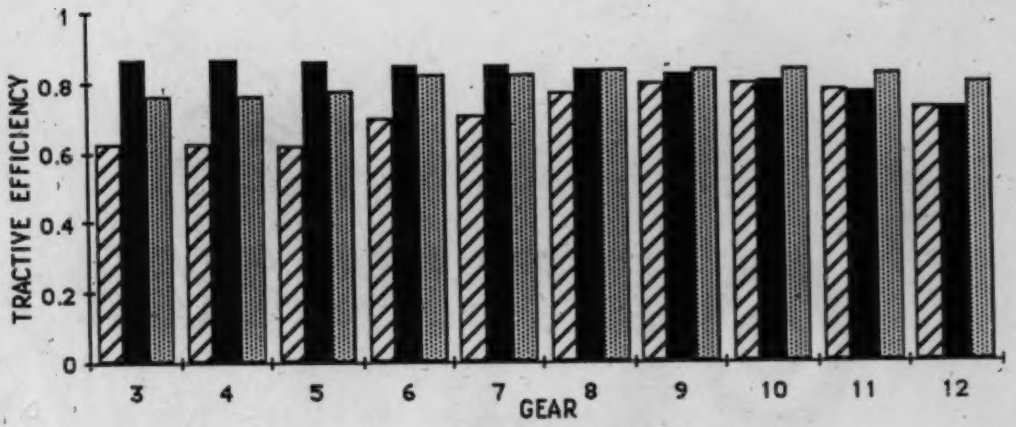


Figure C.29. 2WD/TE/$S_1$/$I_2$

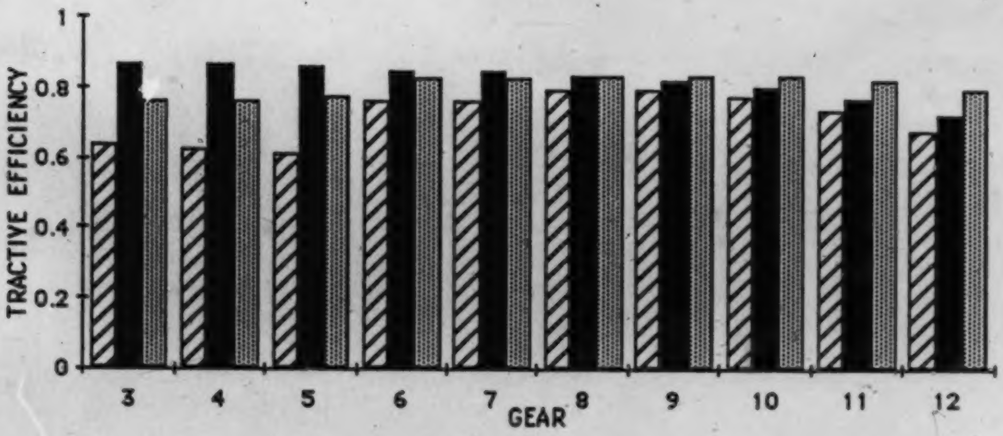


Figure C.30. 2WD/TE/$S_1$/$I_3$

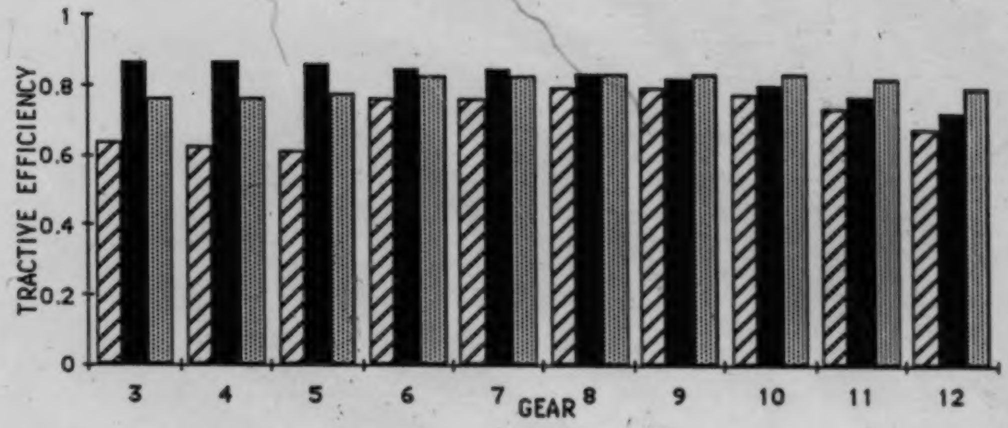


Figure C.31. $2WD/TE/S_2/I_1$

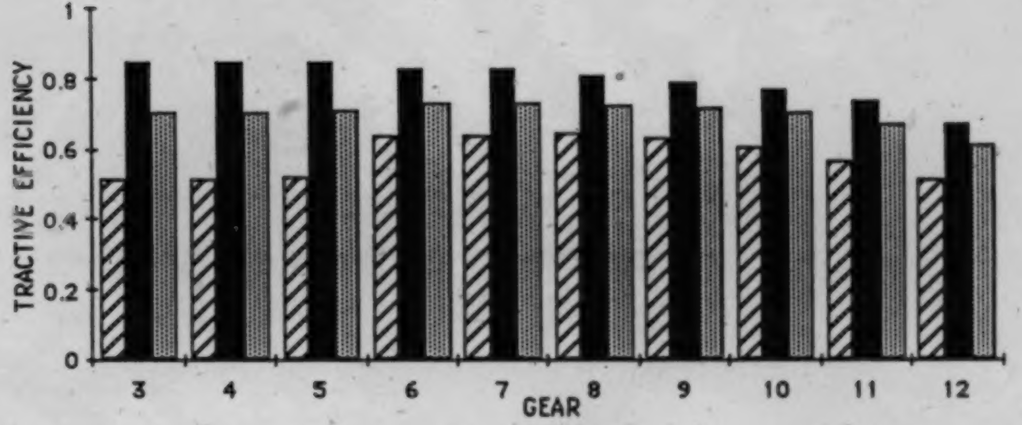


Figure C.32. $2WD/TE/S_2/I_2$

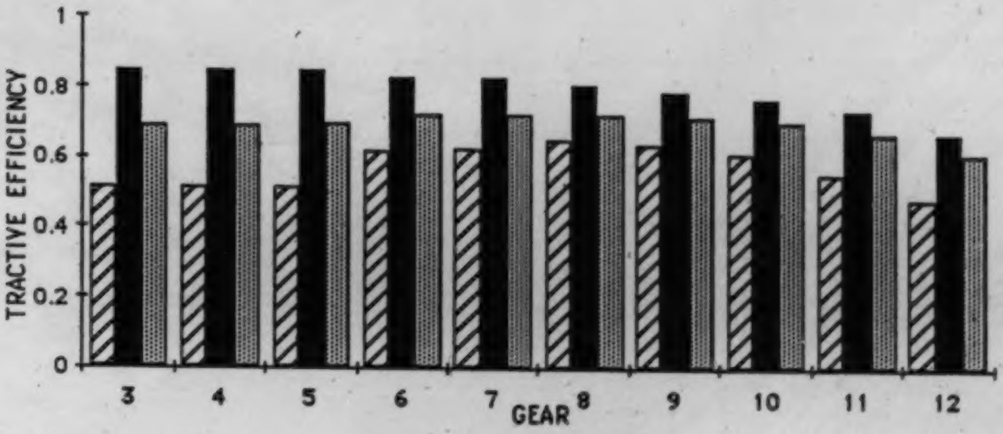


Figure C.33. $2WD/TE/S_2/I_3$

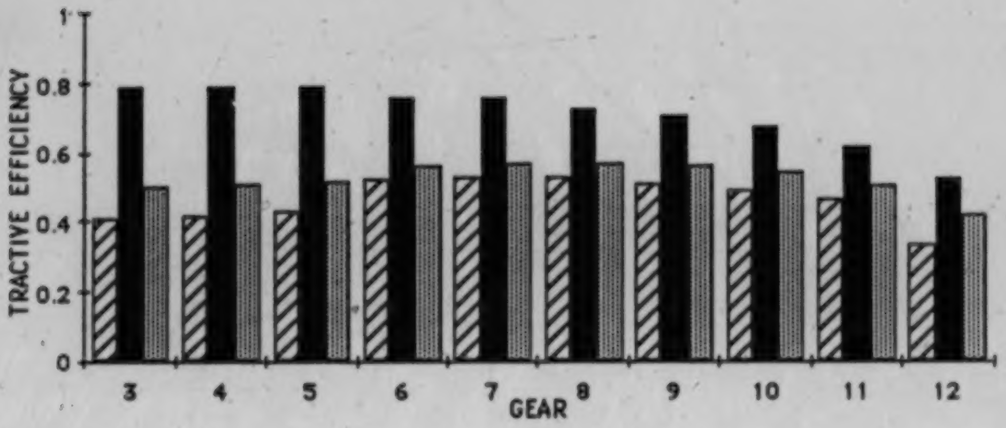


Figure C.34. 2WD/TE/$S_3$/$I_1$

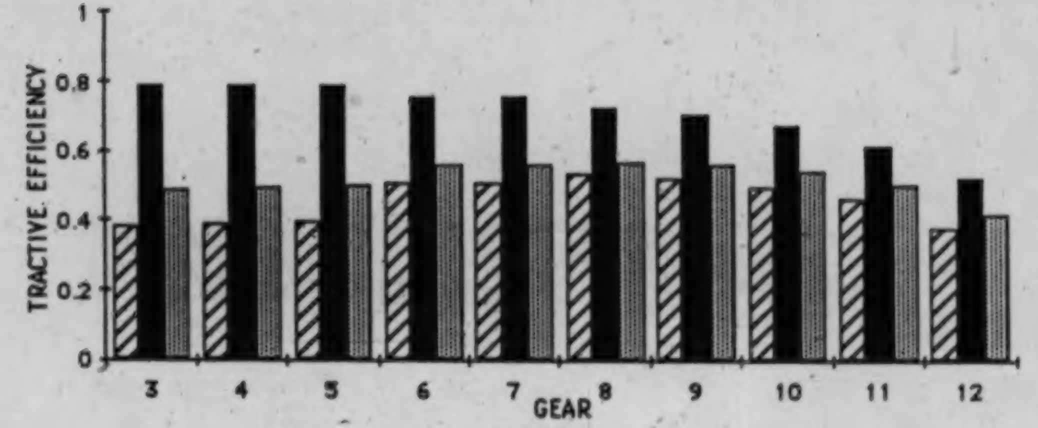


Figure C.35. 2WD/TE/$S_3$/$I_2$

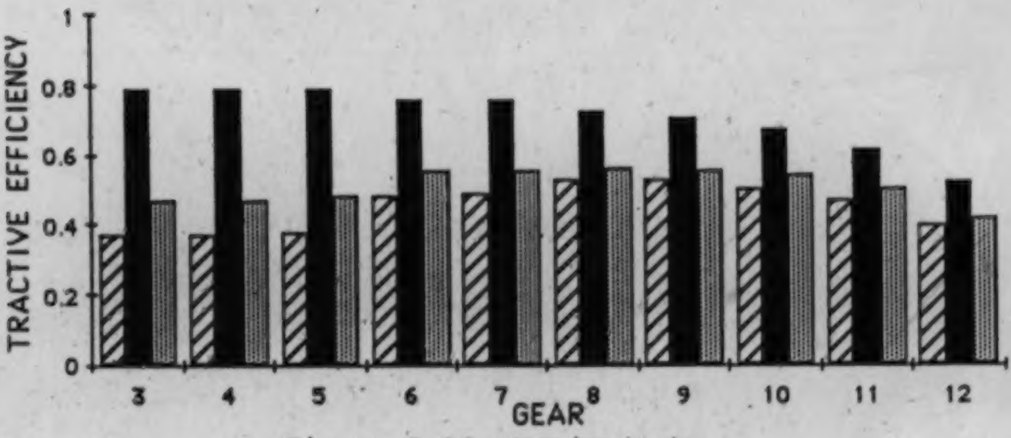


Figure C.36. 2WD/TE/$S_3$/$I_3$

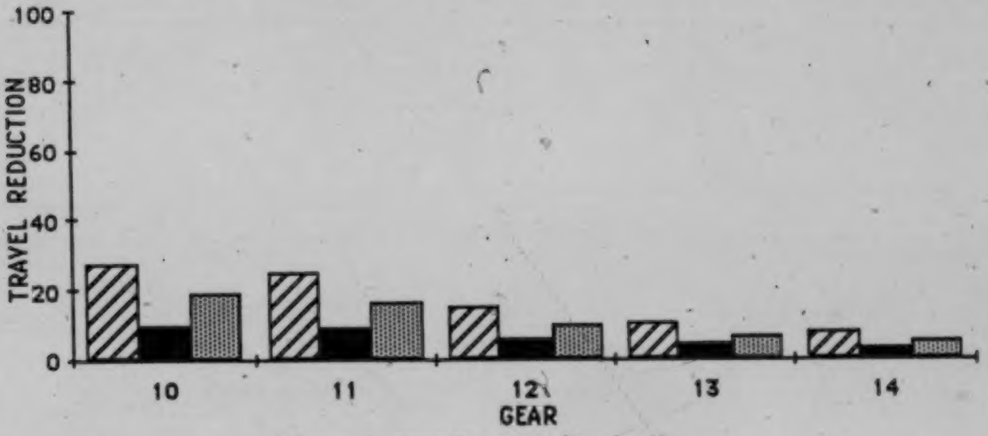


Figure C.37. FWA/TR/$S_1$/$I_1$

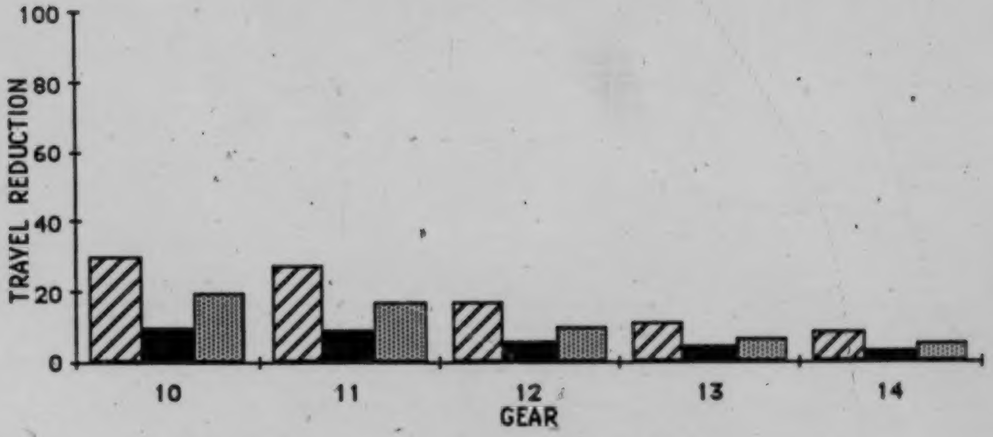


Figure C.38. FWA/TR/$S_1$/$I_2$

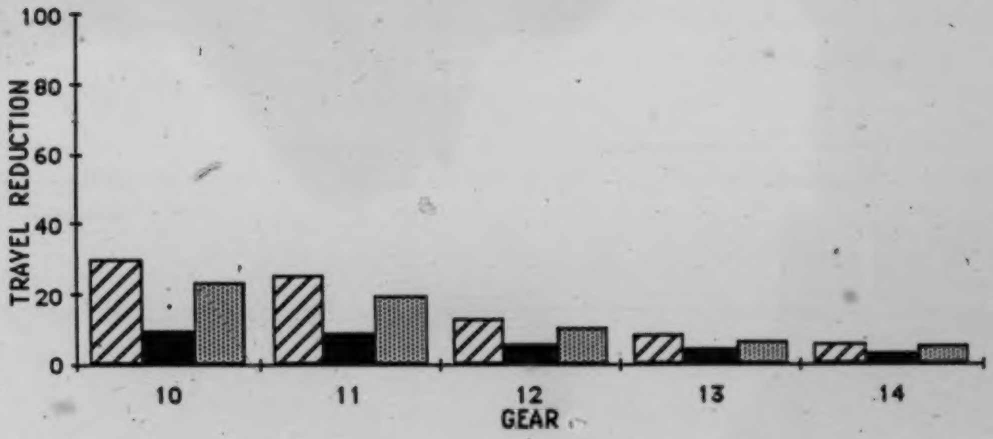


Figure C.39. FWA/TR/$S_1$/$I_3$

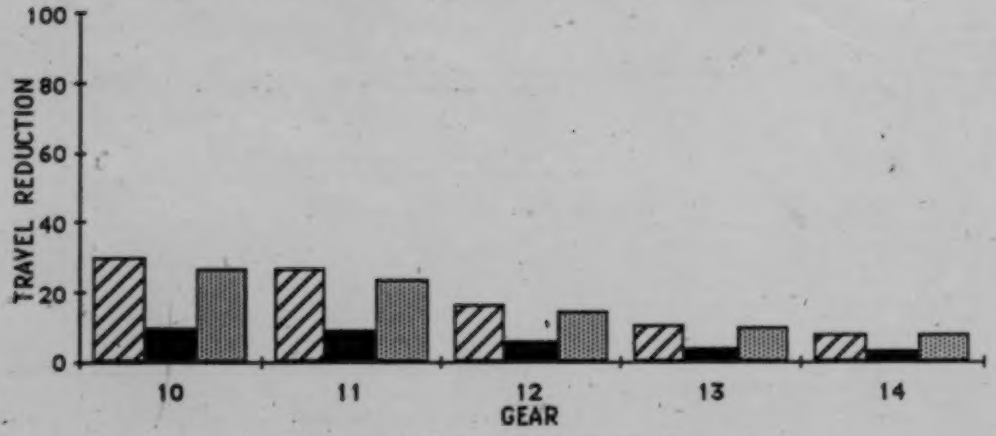


Figure C.40. FWA/TR/$S_2$/$I_1$

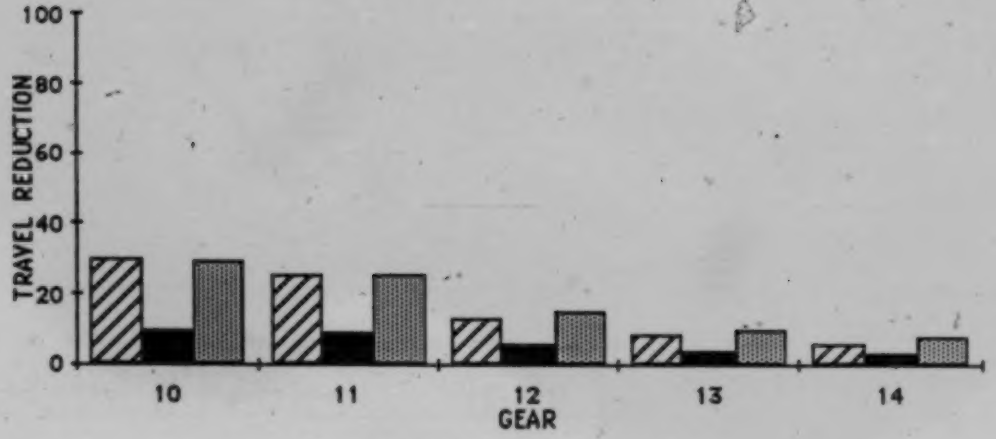


Figure C.41. FWA/TR/$S_2$/$I_2$

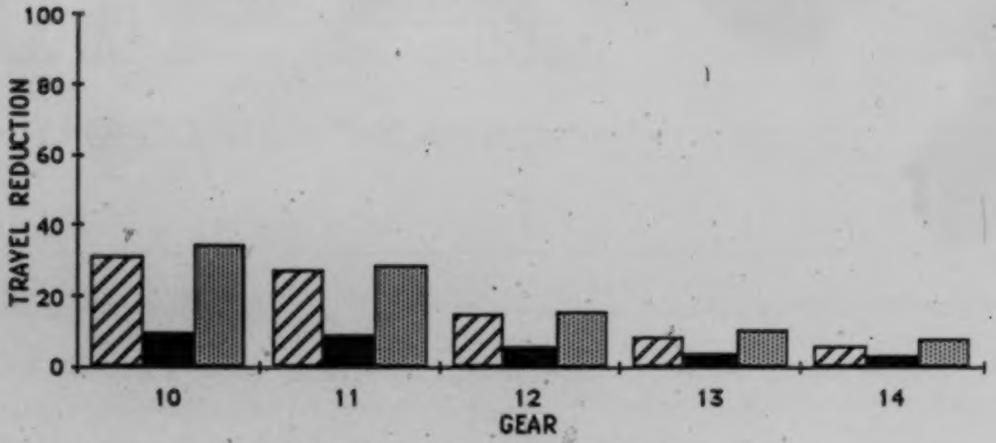


Figure C.42. FWA/TR/$S_2$/$I_3$

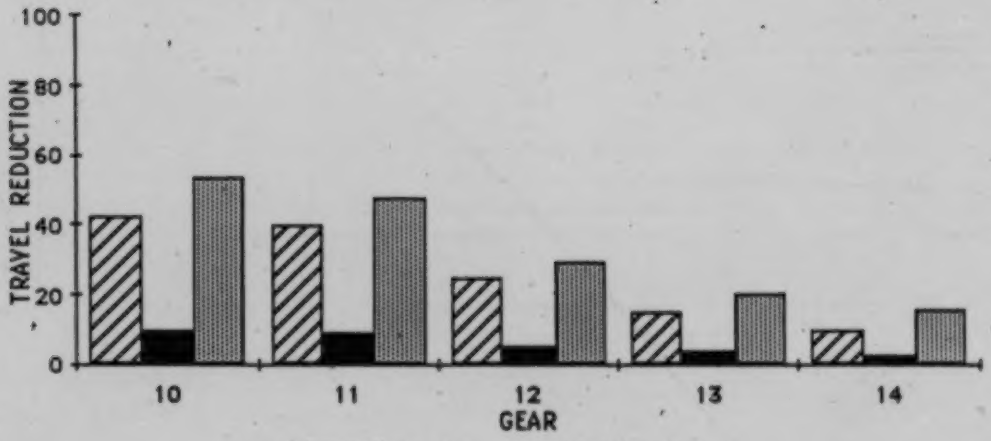


Figure C.43. FWA/TR/$S_3$/$I_1$

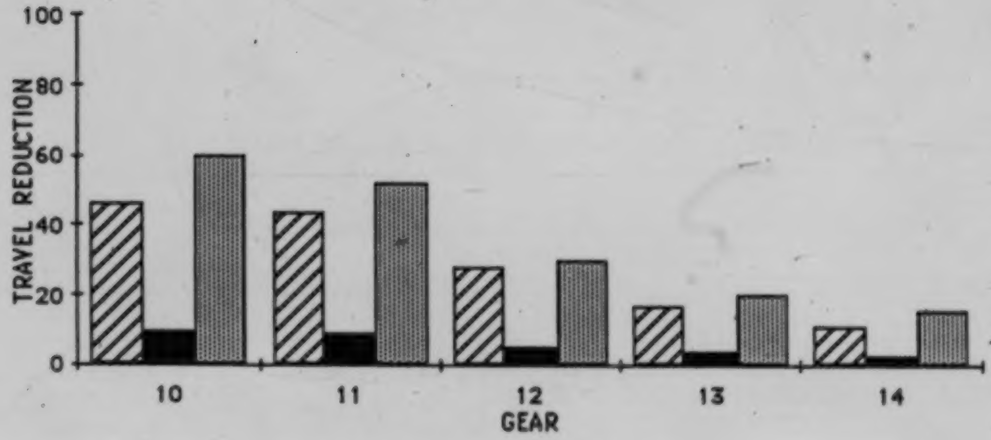


Figure C.44. FWA/TR/$S_3$/$I_2$

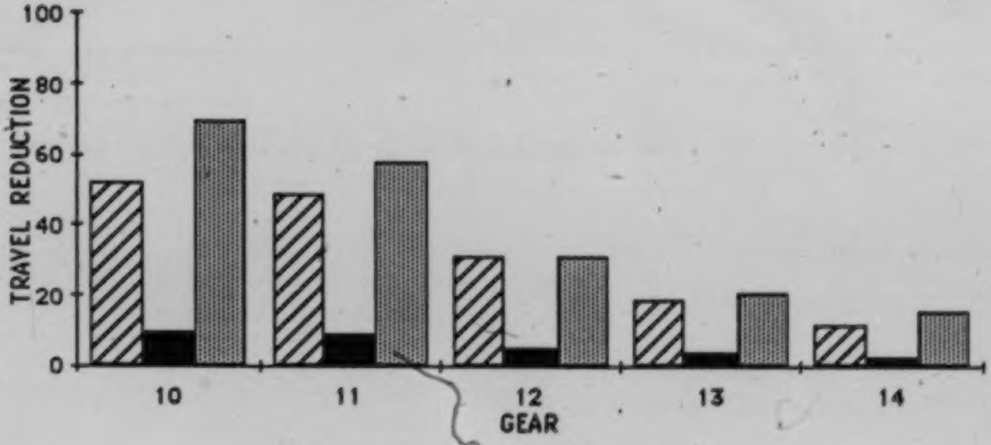


Figure C.45. FWA/TR/$S_3$/$I_3$

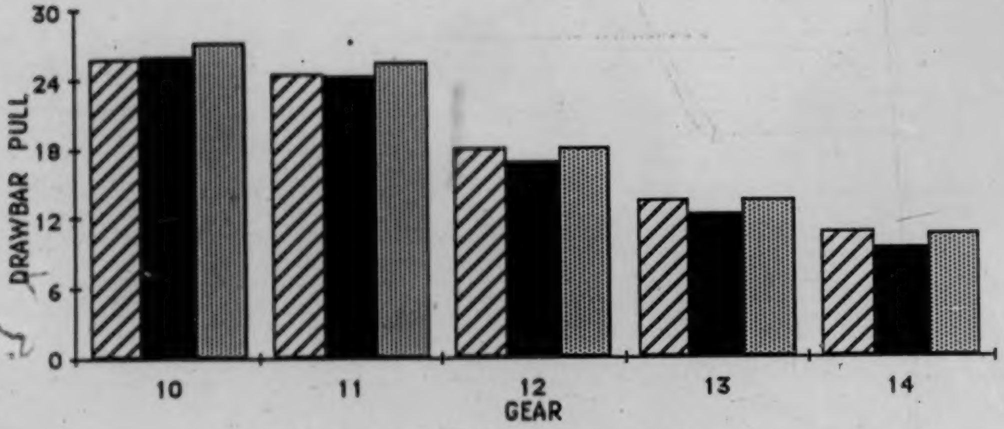


Figure C.46. FWA/DBPL/$S_1$/$I_1$

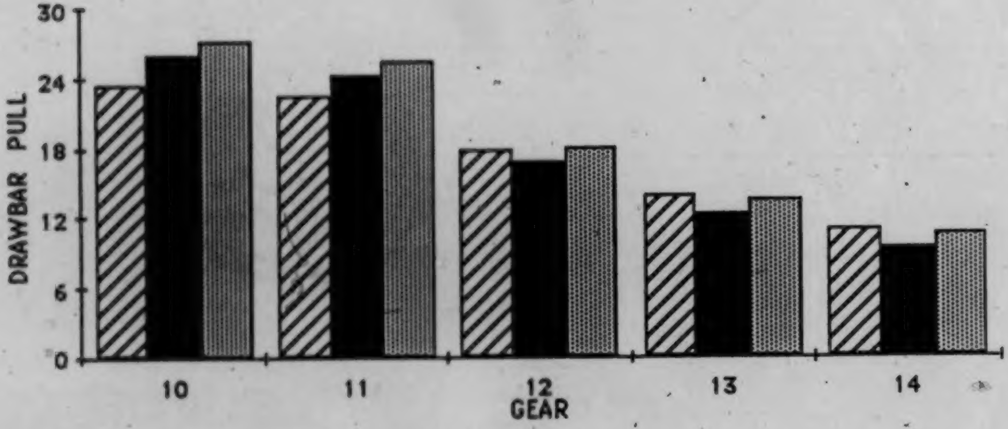


Figure C.47. FWA/DBPL/$S_1$/$I_2$

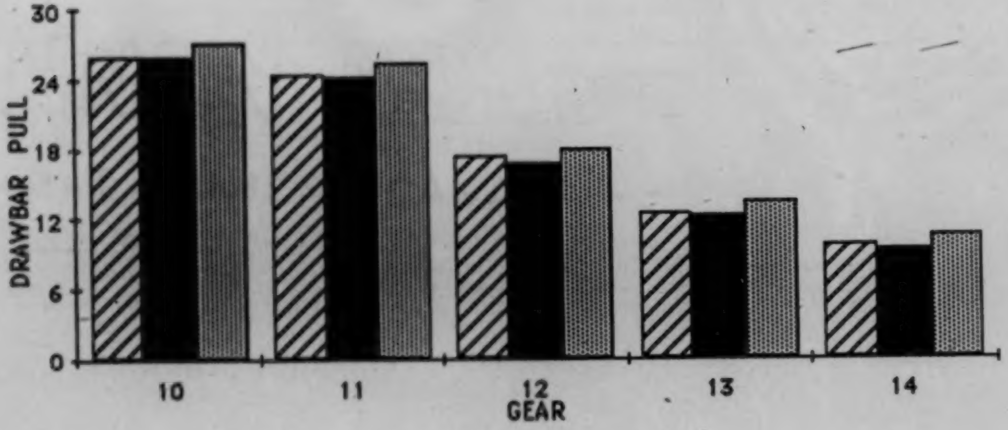


Figure C.48. FWA/DBPL/$S_1$/$I_3$

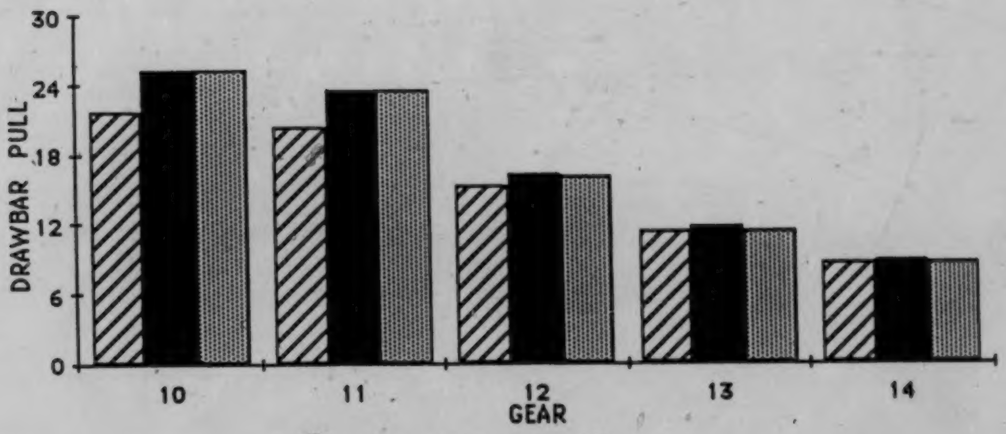


Figure C.49. FWA/DBPL/$S_2$/$I_1$

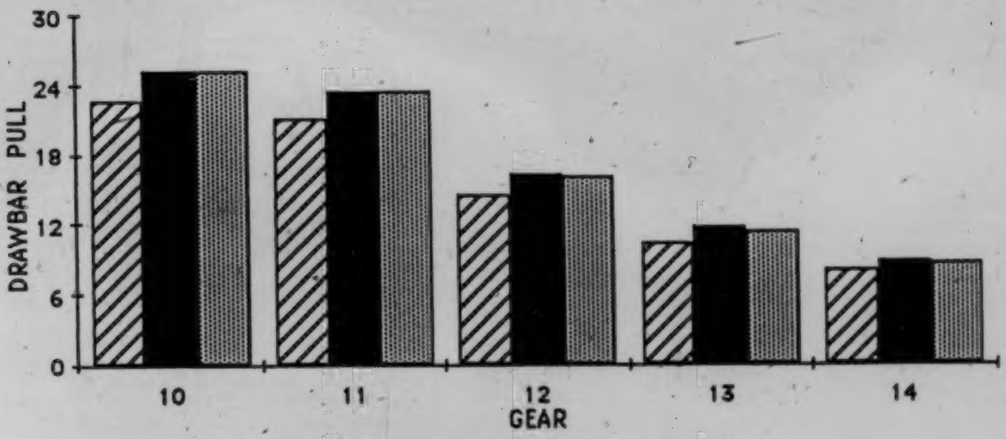


Figure C.50. FWA/DBPL/$S_2$/$I_2$

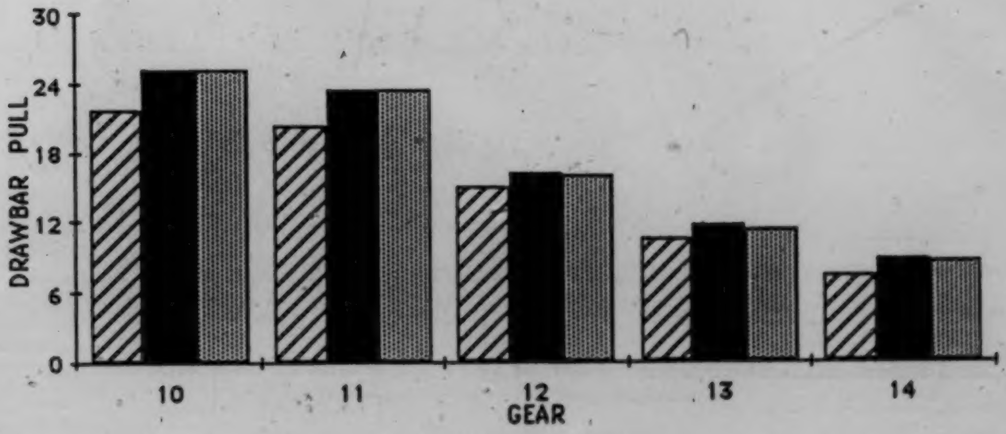


Figure C.51. FWA/DBPL/$S_2$/$I_3$

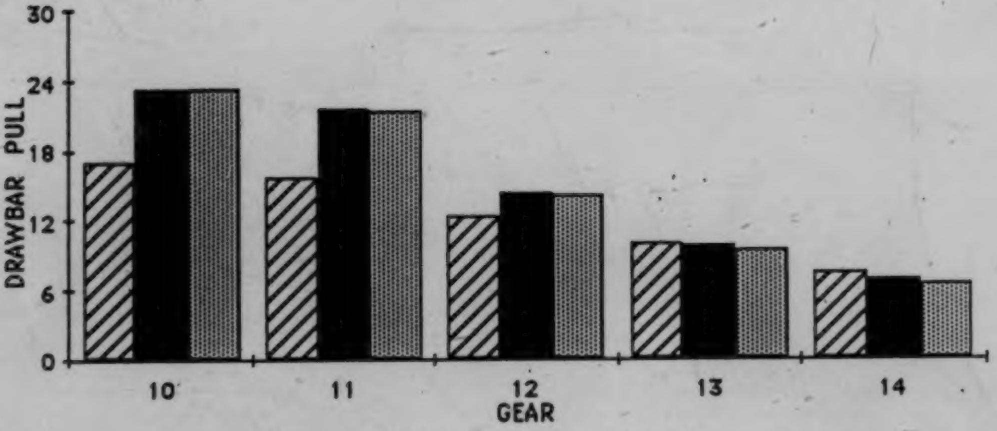


Figure C.52. FWA/DBPL/$S_3/I_1$

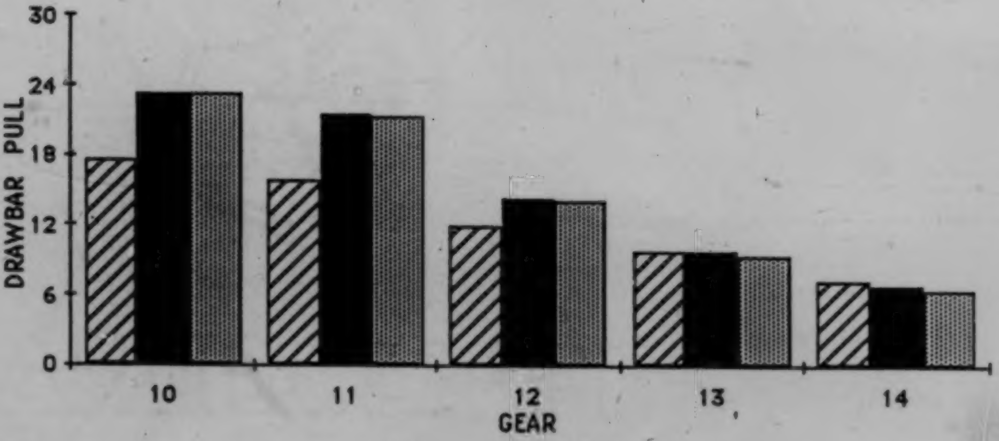


Figure C.53. FWA/DBPL/$S_3/I_2$

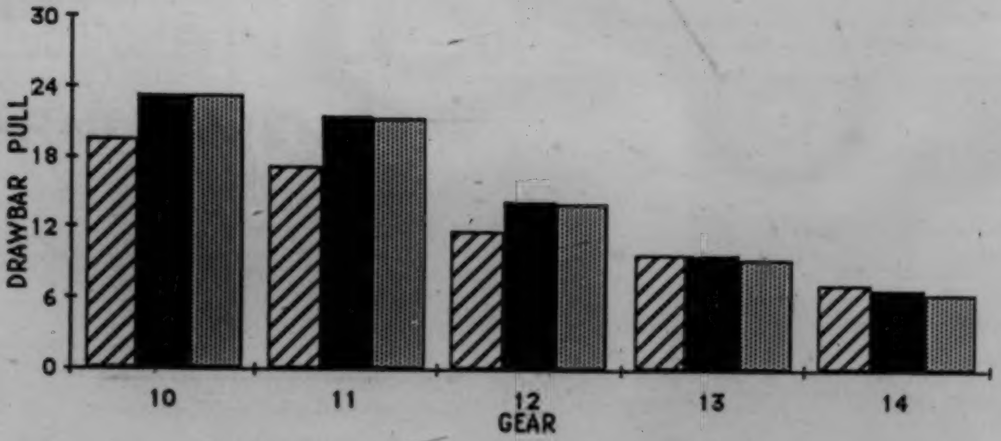


Figure C.54. FWA/DBPL/$S_3/I_3$

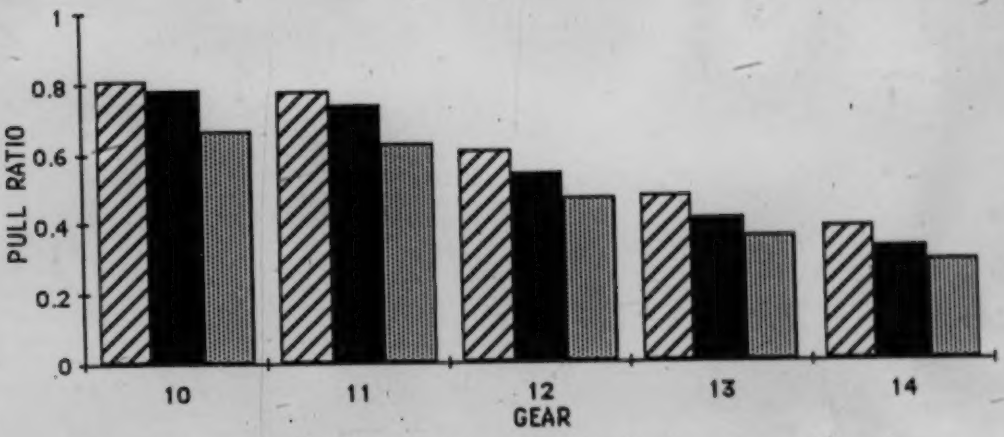


Figure C.55. FWA/PR/$S_1$/$I_1$

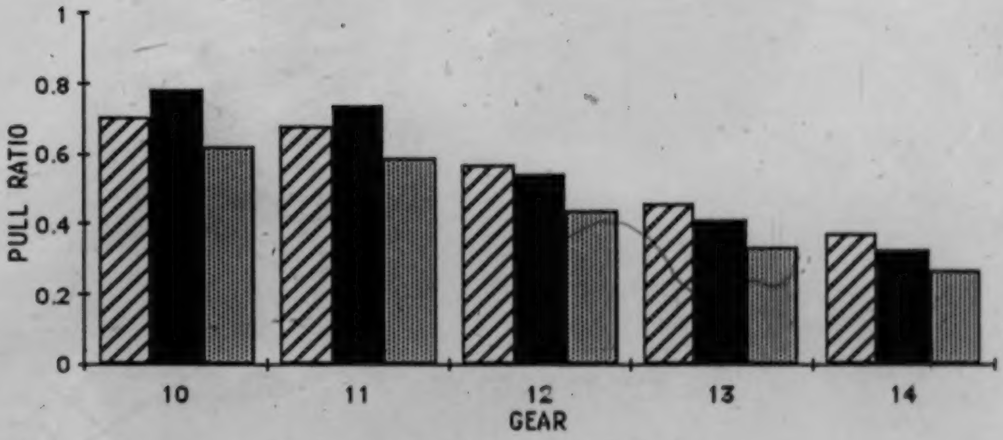


Figure C.56. FWA/PR/$S_1$/$I_2$

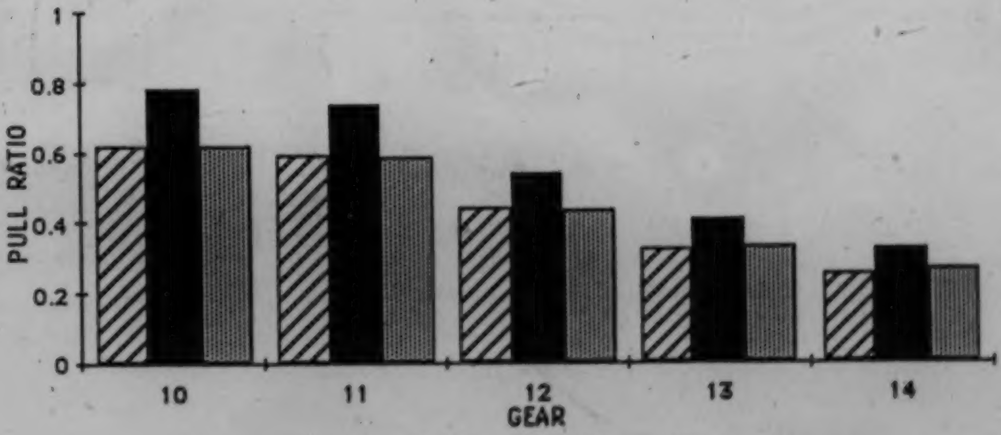


Figure C.57. FWA/PR/$S_1$/$I_3$

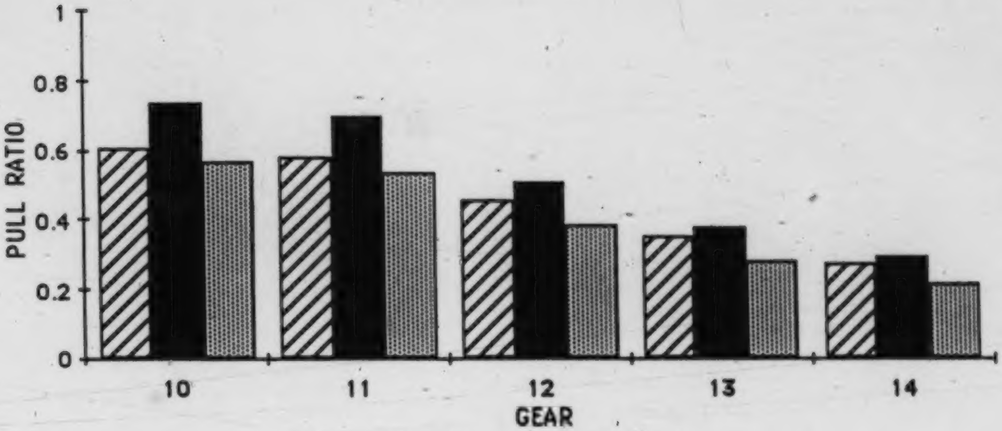


Figure C.58. FWA/PR/$S_2/I_1$

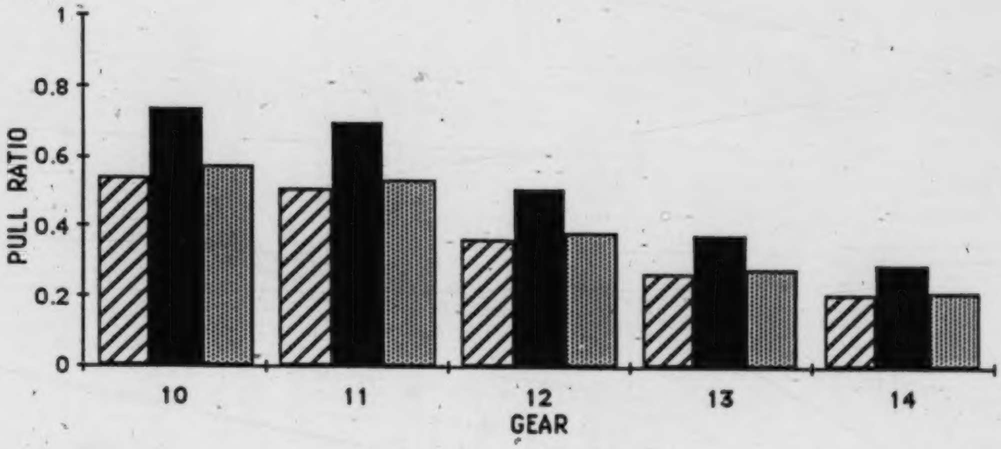


Figure C.59. FWA/PR/$S_2/I_2$

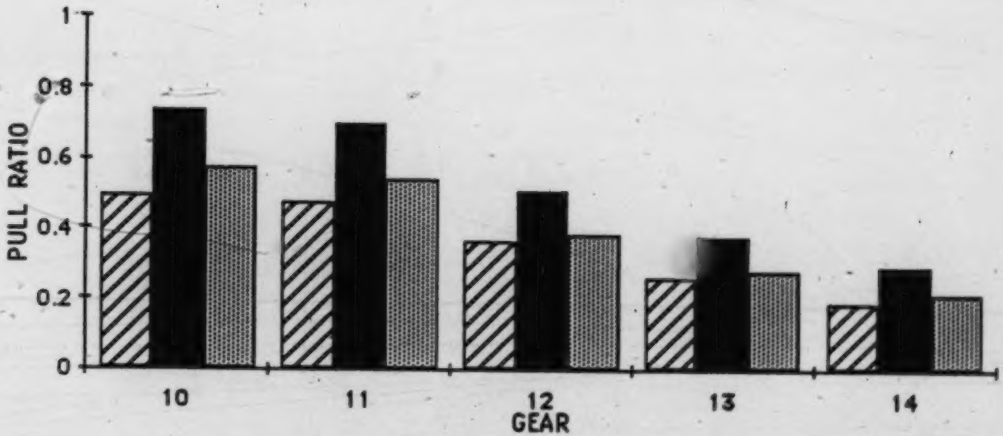


Figure C.60. FWA/PR/$S_2/I_3$

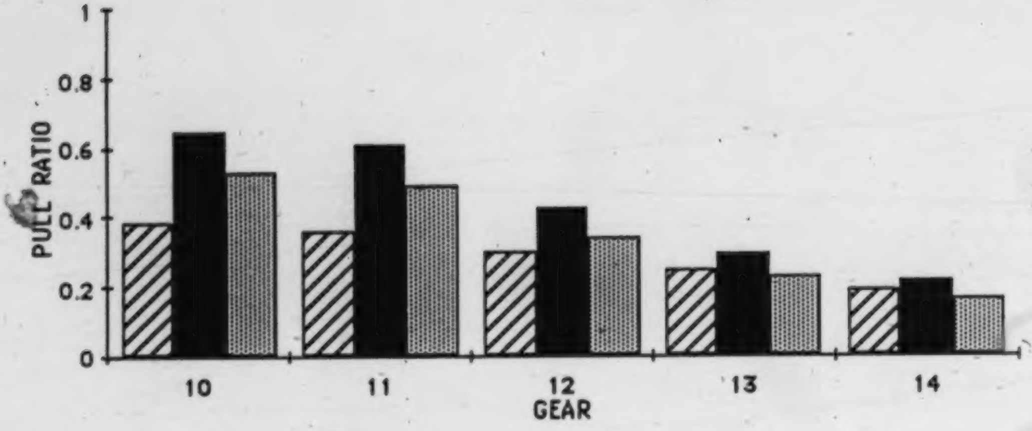


Figure C.61. FWA/PR/$S_3$/$I_1$

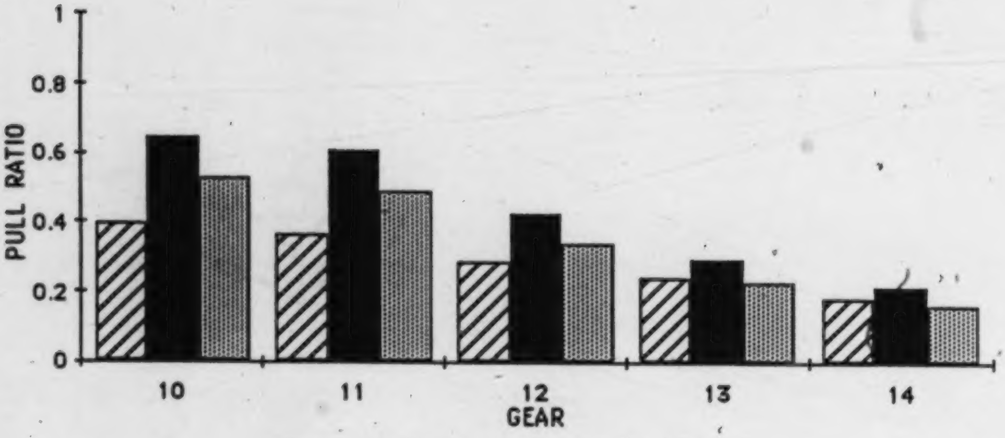


Figure C.62. FWA/PR/$S_3$/$I_2$

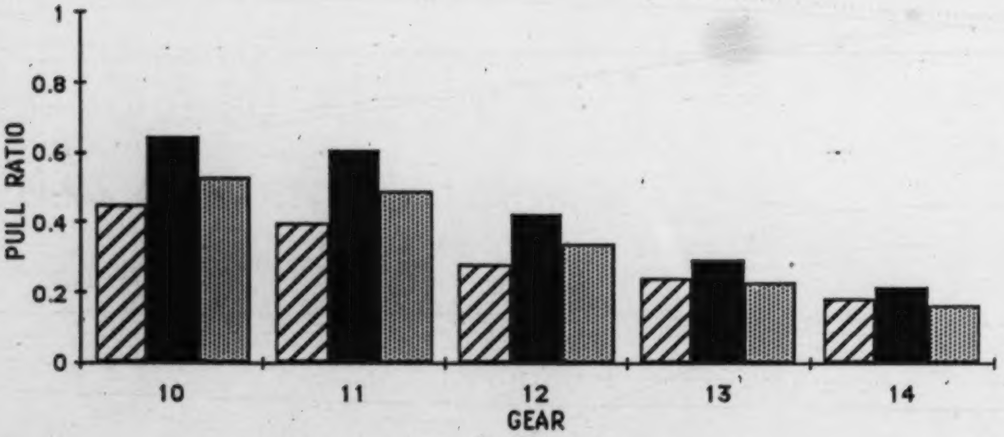


Figure C.63. FWA/PR/$S_3$/$I_3$

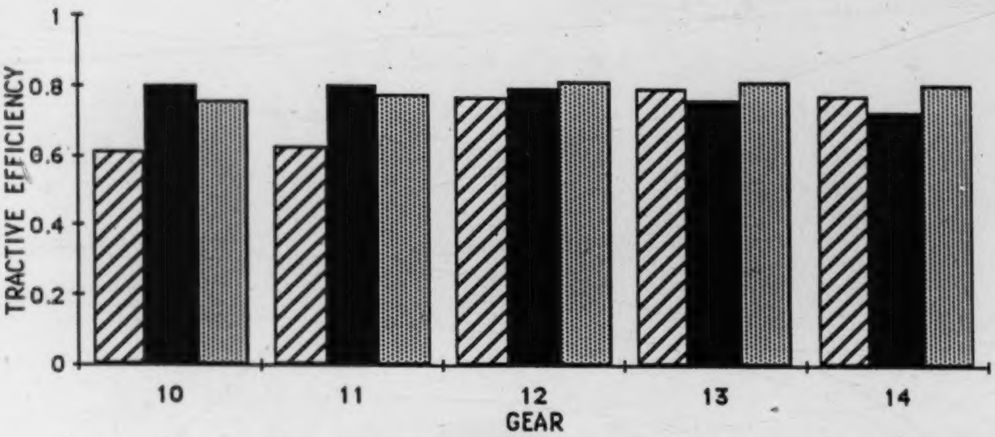


Figure C.64. FWA/TE/$S_1$/$I_1$

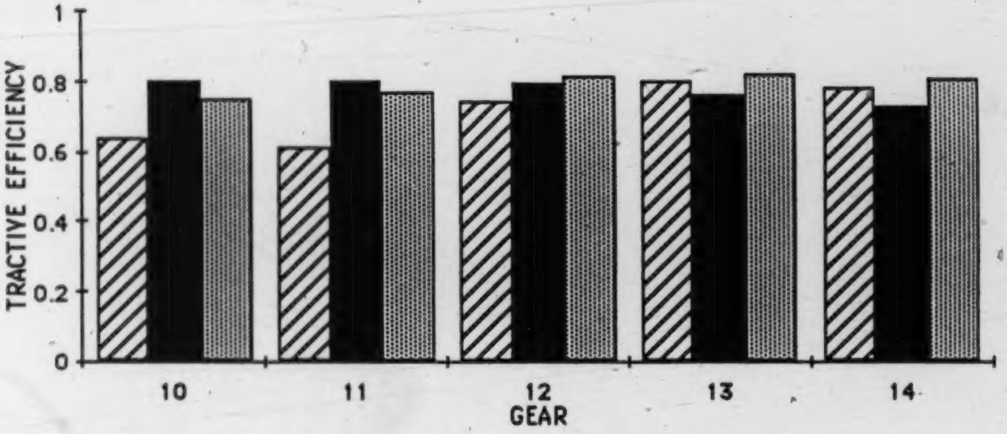


Figure C.65. FWA/TE/$S_1$/$I_2$

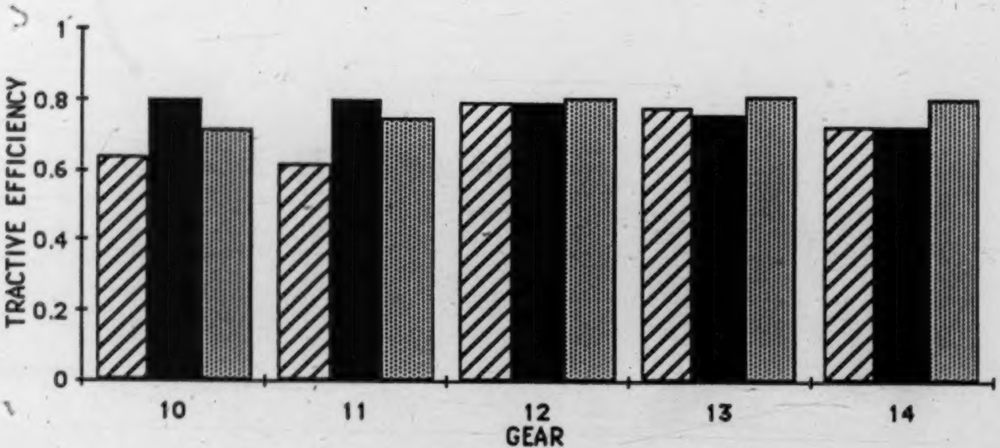


Figure C.66. FWA/TE/$S_1$/$I_3$

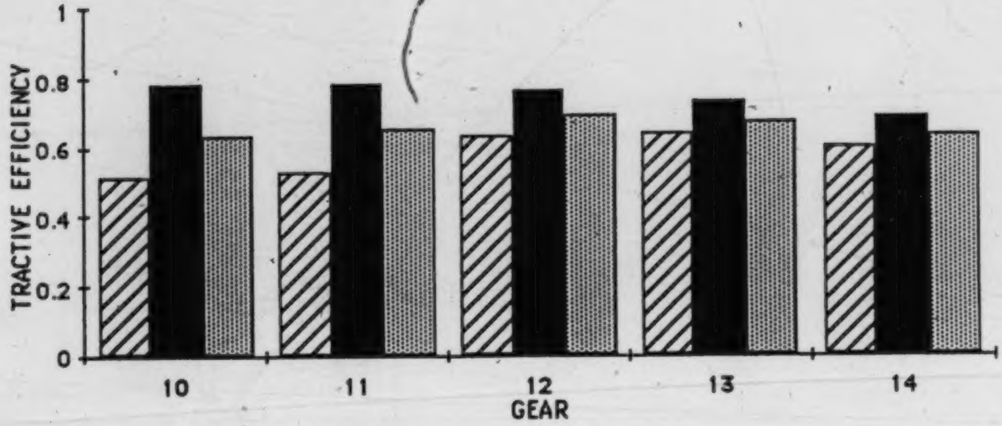


Figure C.67. FWA/TE/$S_2/I_1$

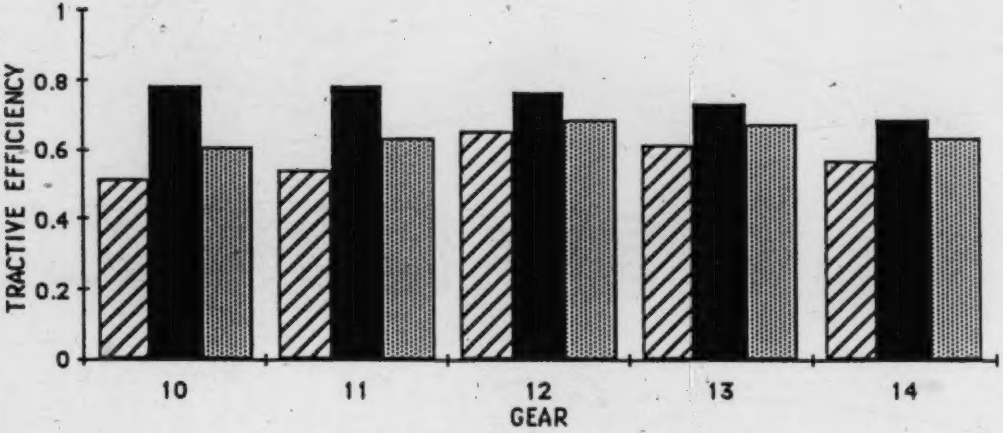


Figure C.68. FWA/TE/$S_2/I_2$

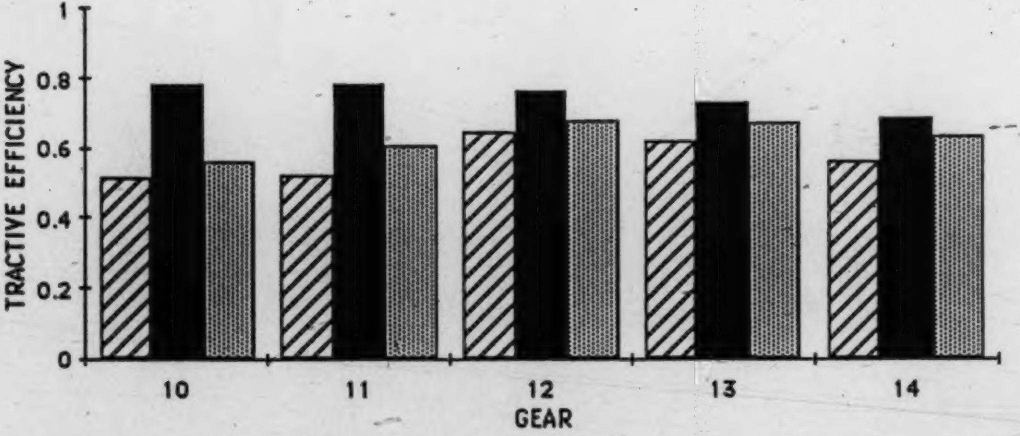


Figure C.69. FWA/TE/$S_2/I_3$

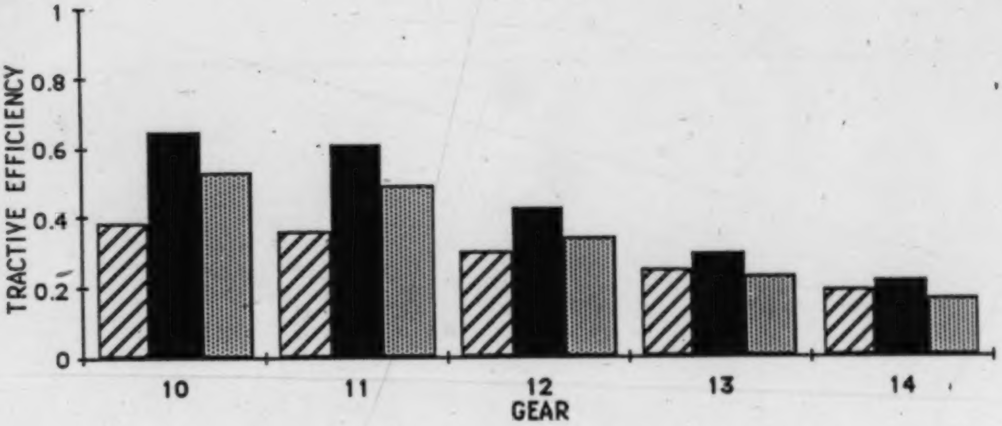


Figure C.70. FWA/TE/$S_3$/$I_1$

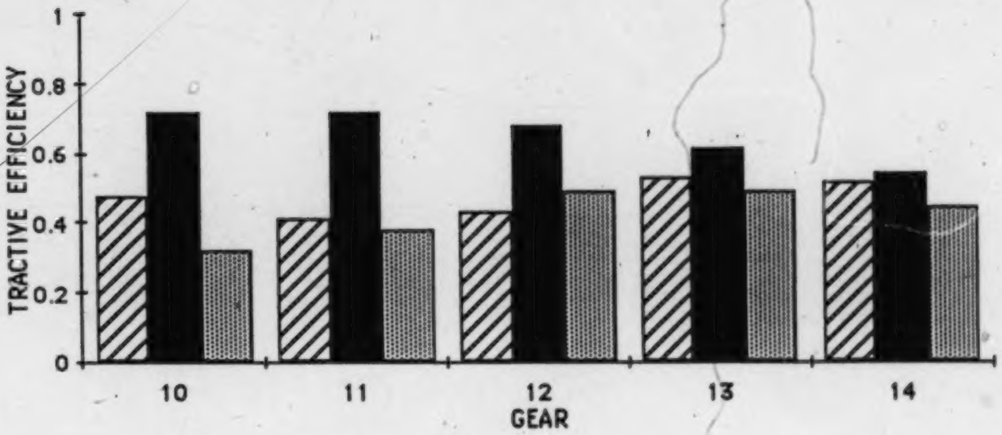


Figure C.71. FWA/TE/$S_3$/$I_2$

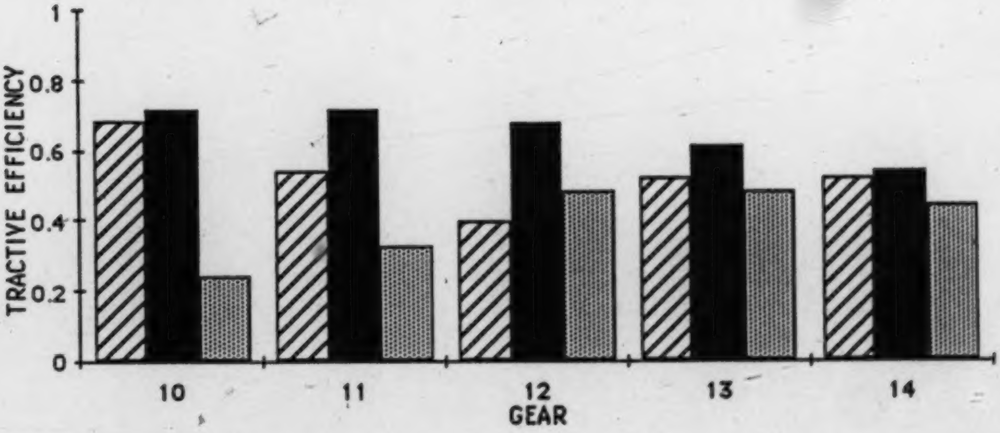


Figure C.72. FWA/TE/$S_3$/$I_3$

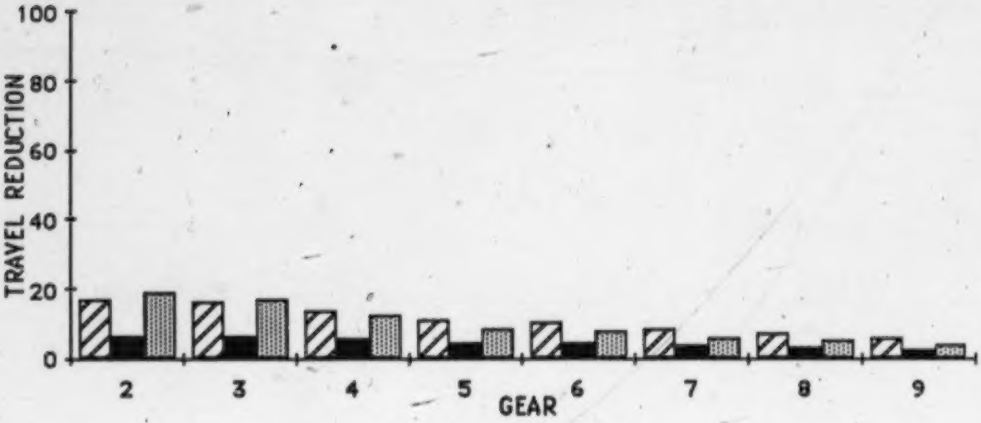


Figure C.73. 4WD/TR/$S_1$/$I_1$

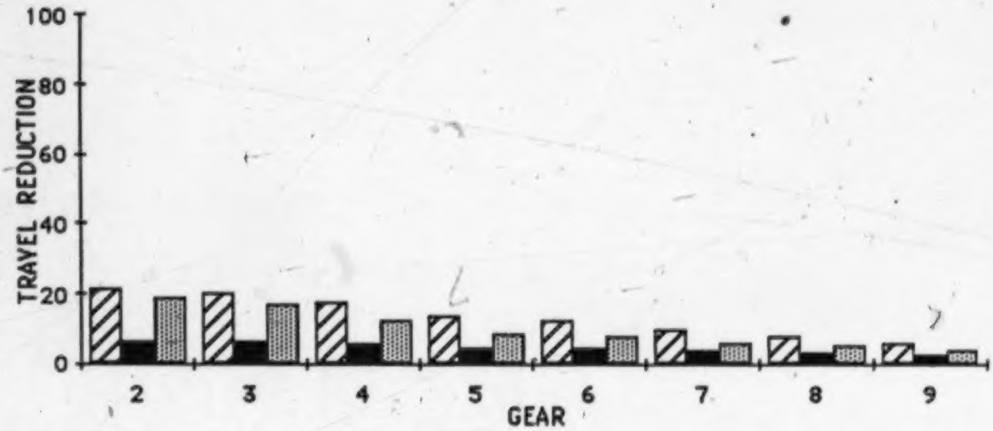


Figure C.74. 4WD/TR/$S_1$/$I_2$

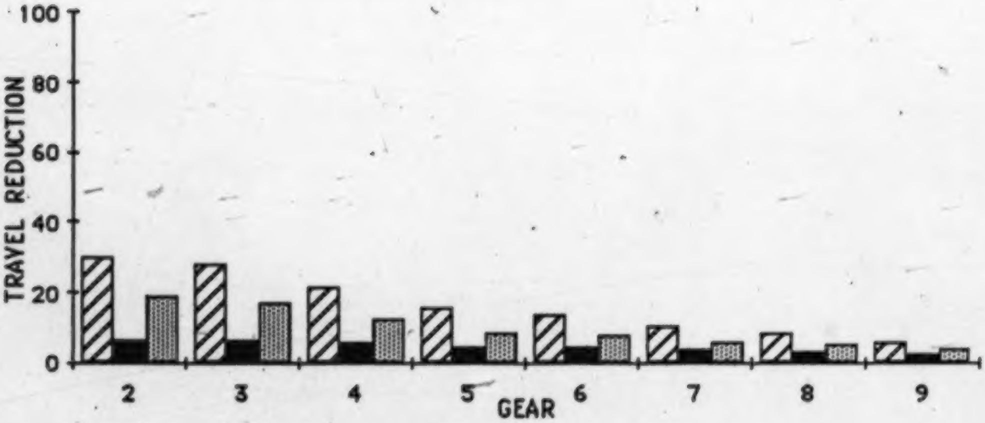


Figure C.75. 4WD/TR/$S_1$/$I_3$

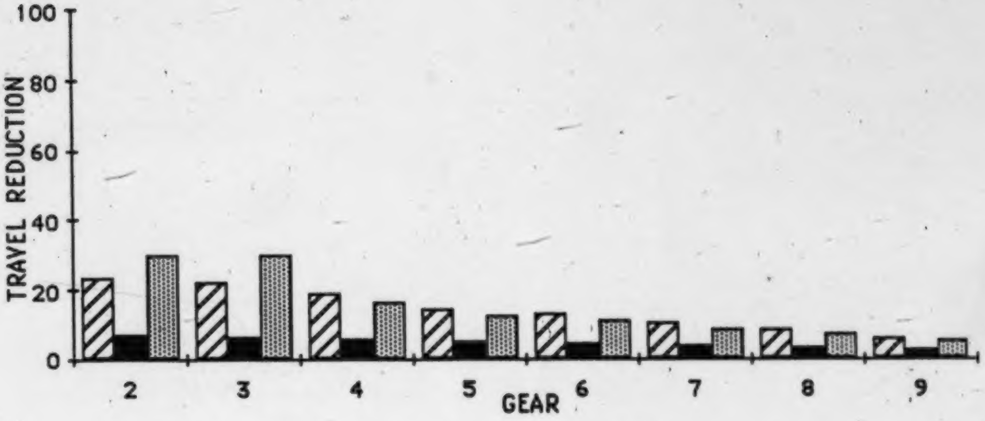


Figure C.76. 4WD/TR/$S_2$/$I_1$

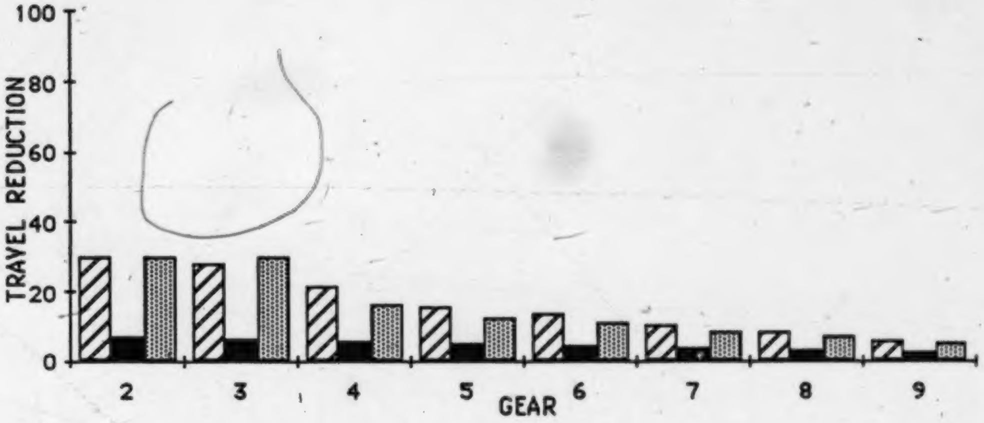


Figure C.77. 4WD/TR/$S_2$/$I_2$

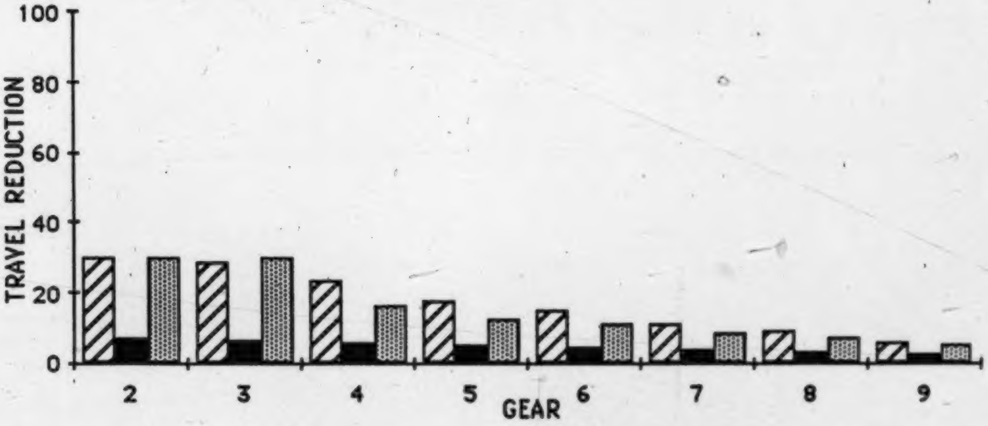


Figure C.78. 4WD/TR/$S_2$/$I_3$

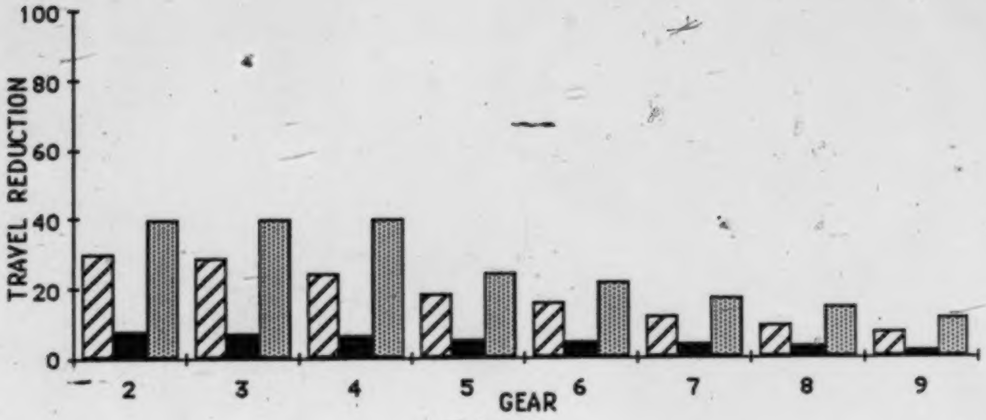


Figure C.79. 4WD/TR/$S_3$/$I_1$

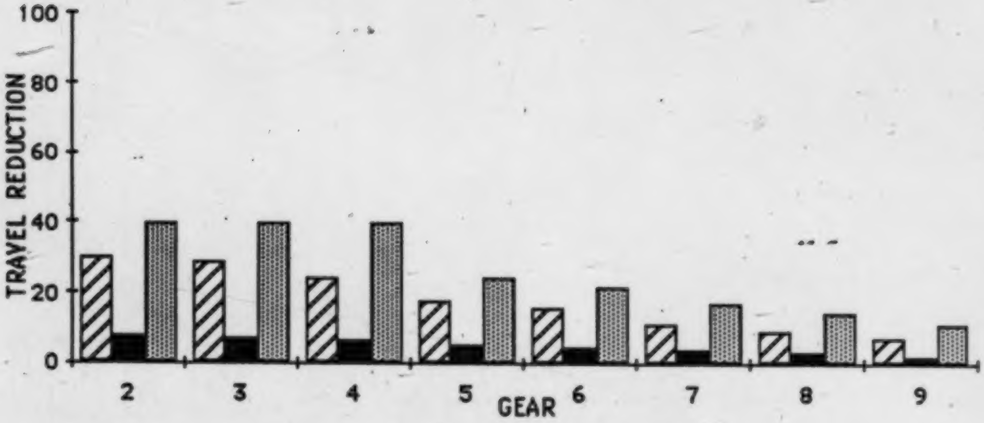


Figure C.80. 4WD/TR/$S_3$/$I_2$

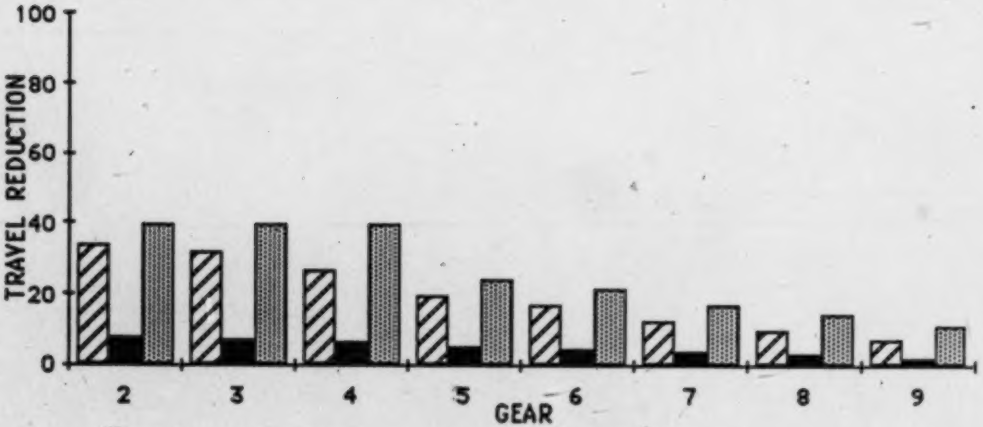


Figure C.81. 4WD/TR/$S_3$/$I_3$

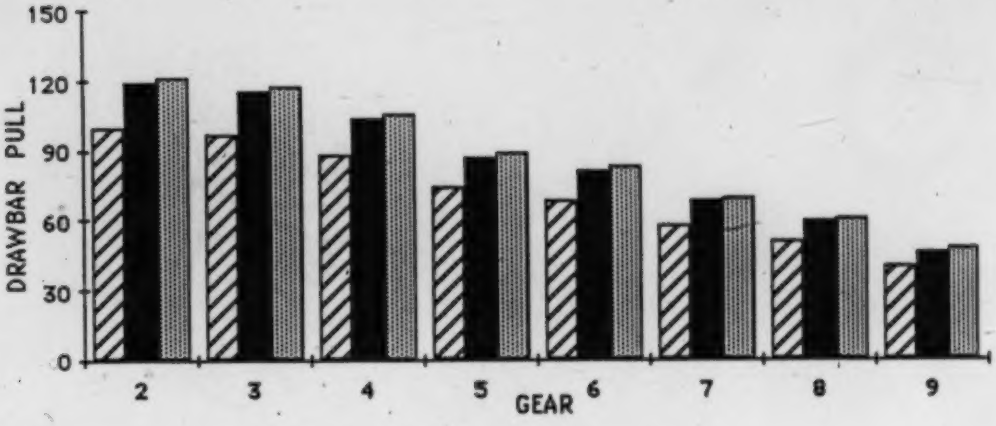


Figure C.82. 4WD/DBPL/$S_1$/$I_1$

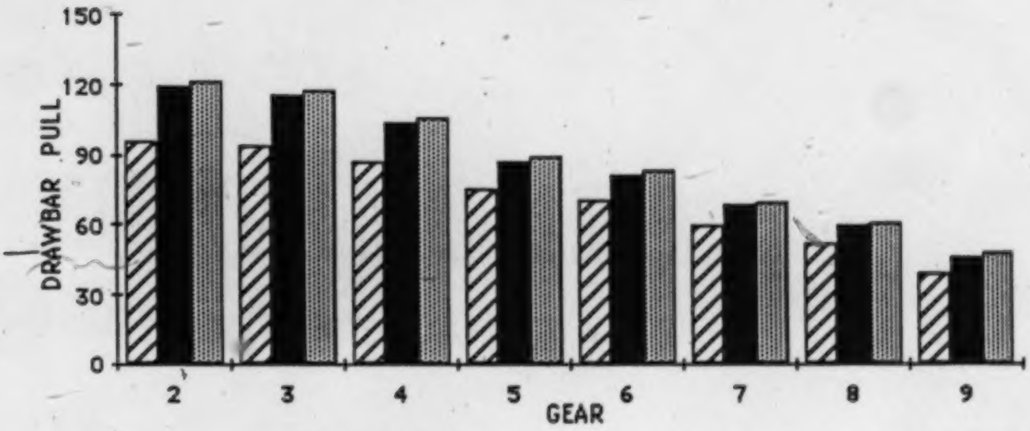


Figure C.83. 4WD/DBPL/$S_1$/$I_2$

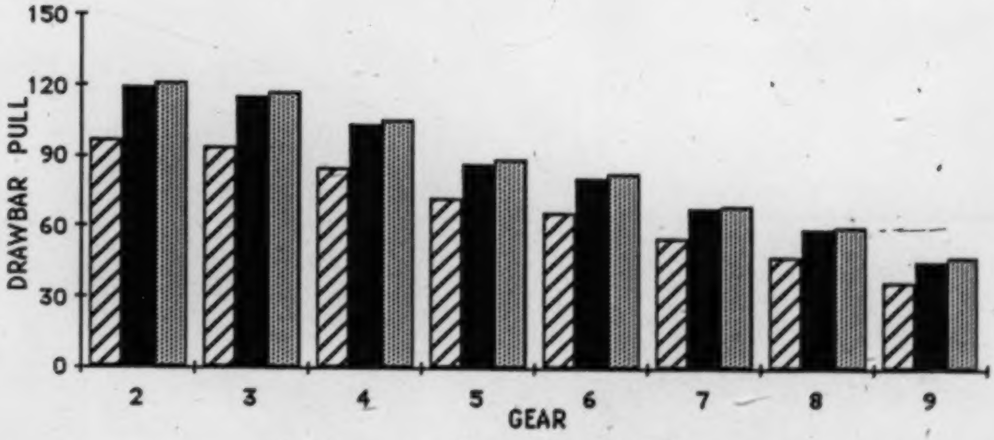


Figure C.84. 4WD/DBPL/$S_1$/$I_3$

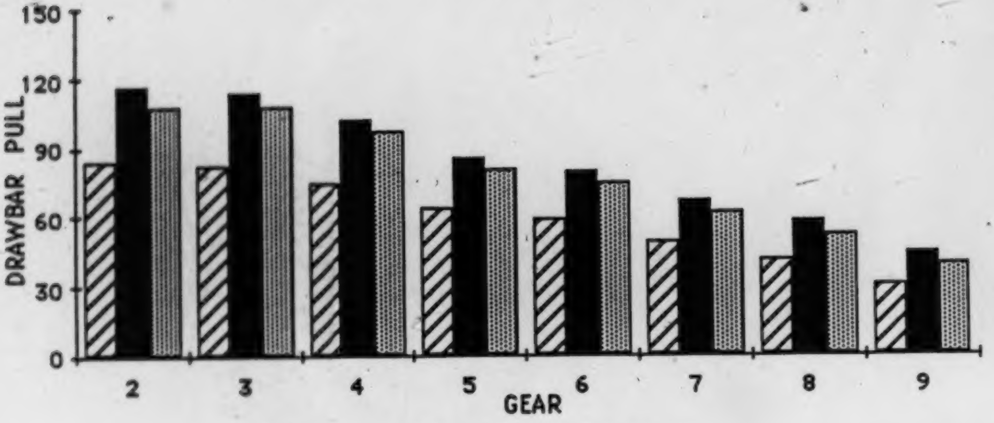


Figure C.85. 4WD/DBPL/$S_2$/$I_1$

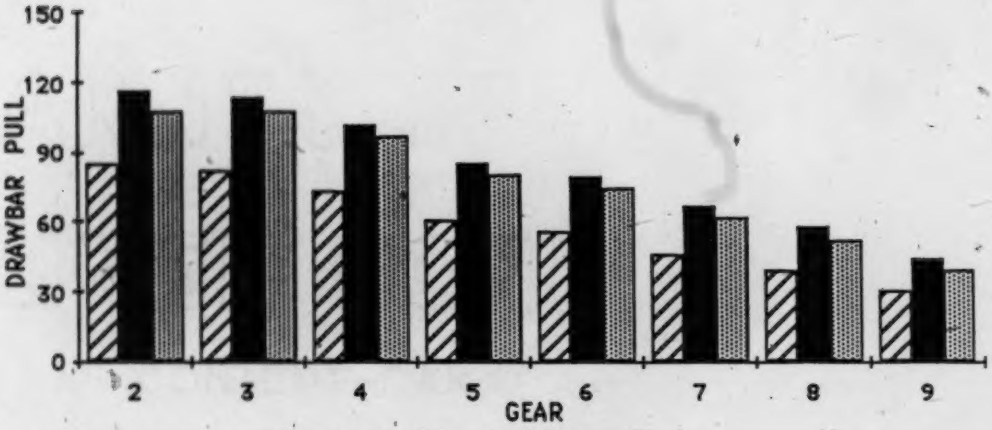


Figure C.86. 4WD/DBPL/$S_2$/$I_2$

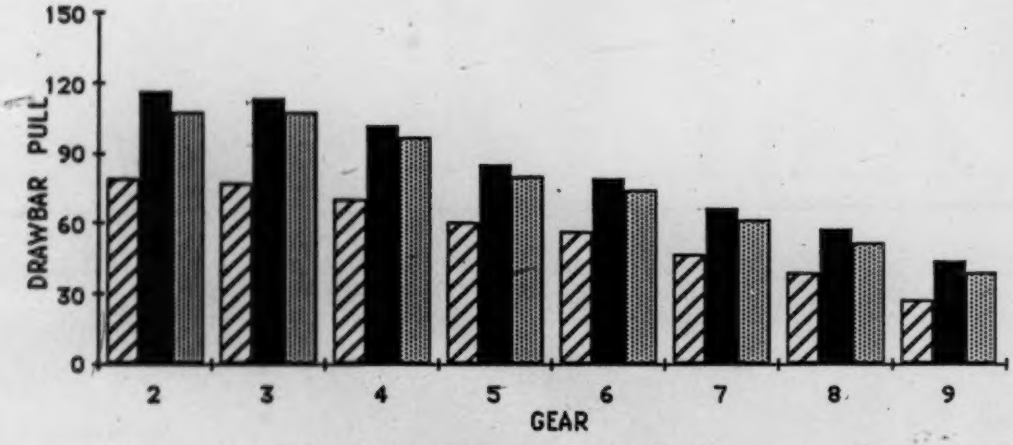


Figure C.87. 4WD/DBPL/$S_2$/$I_3$

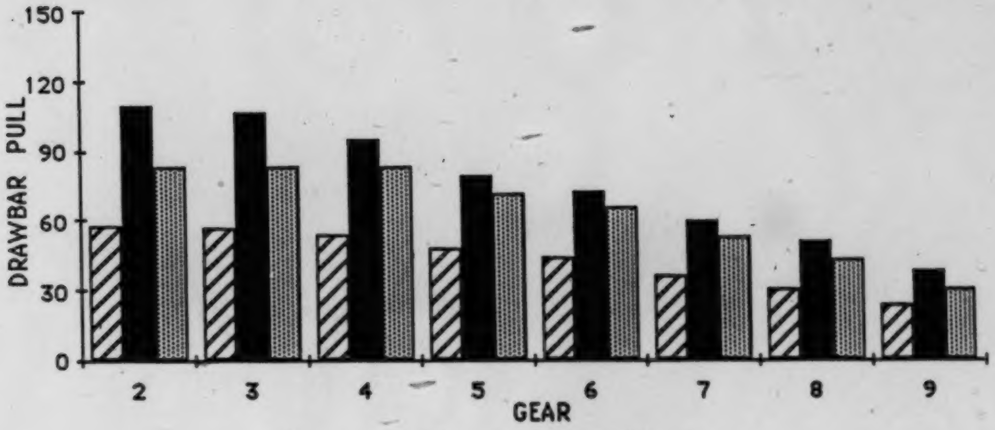


Figure C.88. 4WD/DBPL/$S_3$/$I_1$

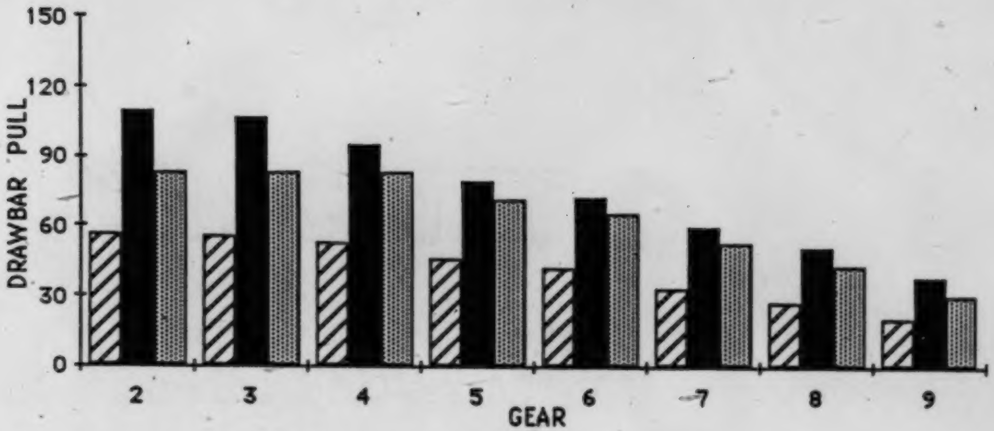


Figure C.89. 4WD/DBPL/$S_3$/$I_2$

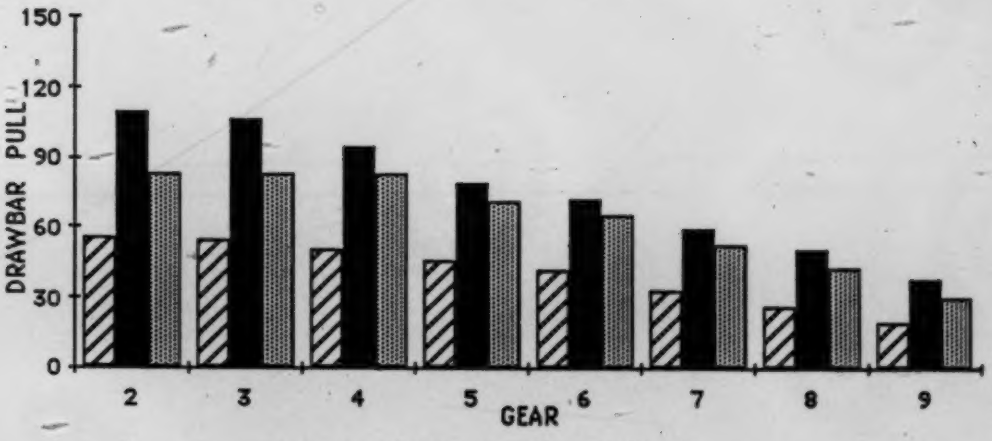


Figure C.90. 4WD/DBPL/$S_3$/$I_3$

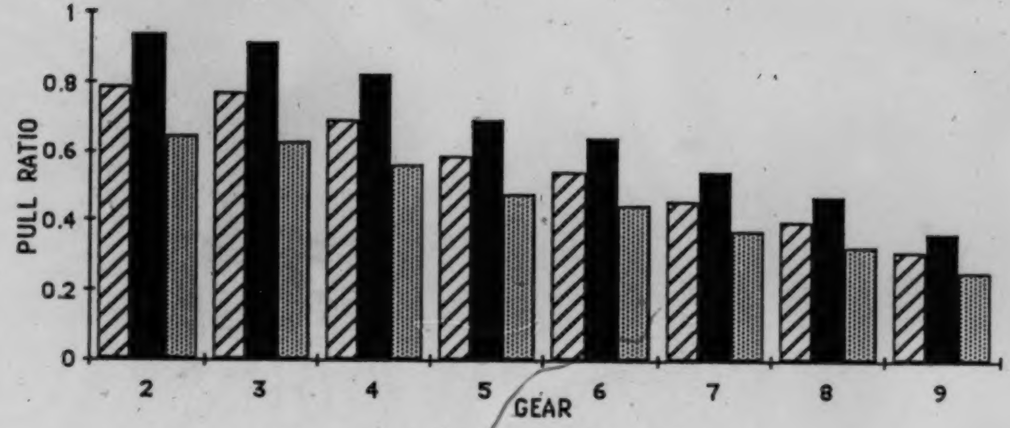


Figure C.91. 4WD/PR/$S_1$/$I_1$

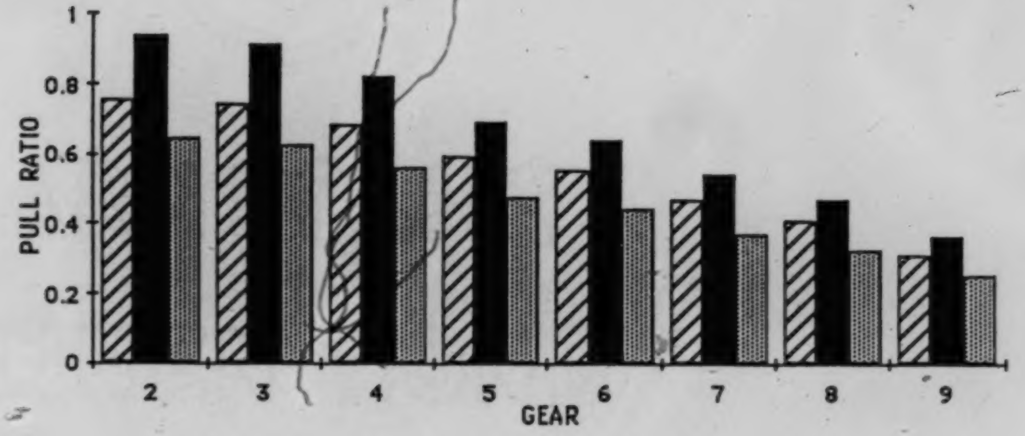


Figure C.92. 4WD/PR/$S_1$/$I_2$

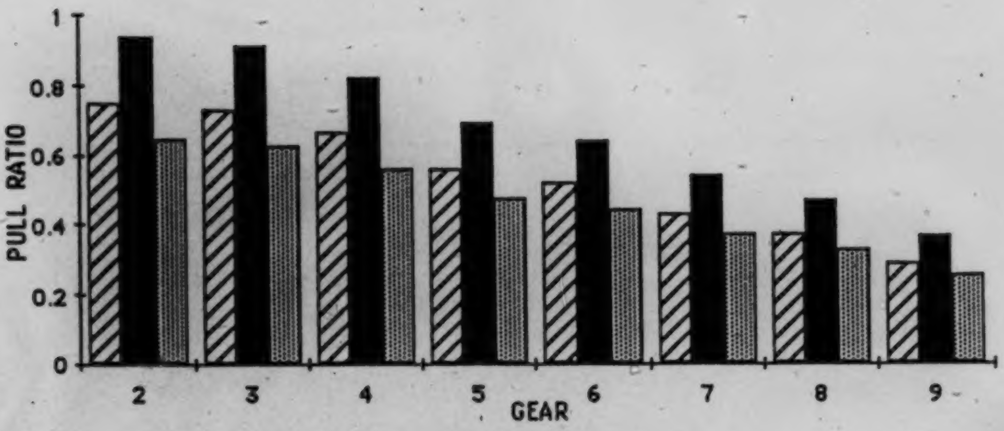


Figure C.93. 4WD/PR/$S_1$/$I_3$

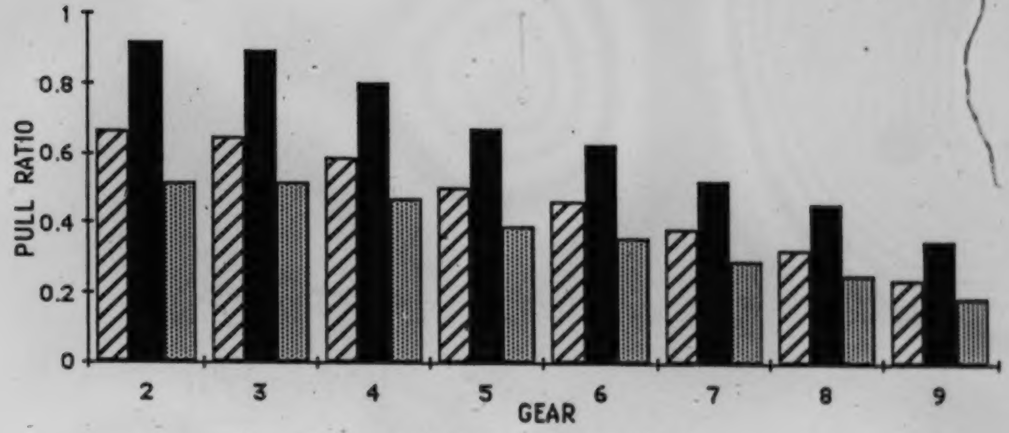


Figure C.94. 4WD/PR/$S_2$/$I_1$

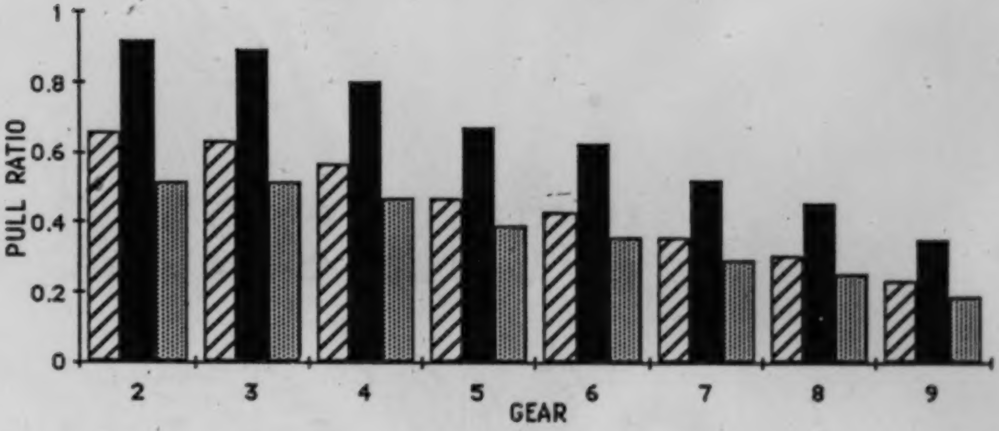


Figure C.95. 4WD/PR/$S_2$/$I_2$

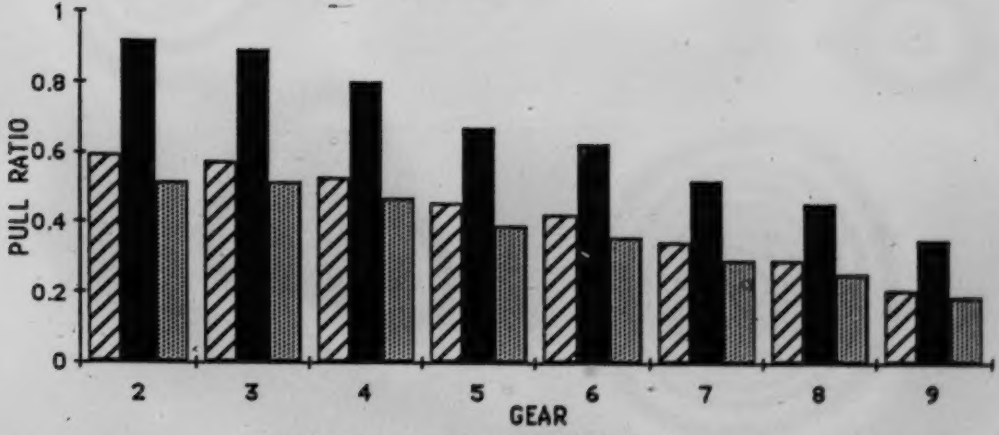


Figure C.96. 4WD/PR/$S_2$/$I_3$

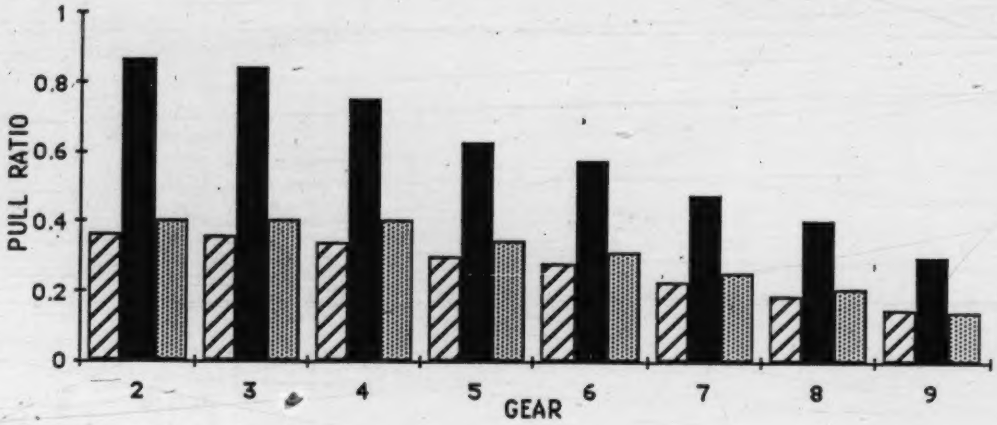


Figure C.97. 4WD/PR/$S_3$/$I_1$

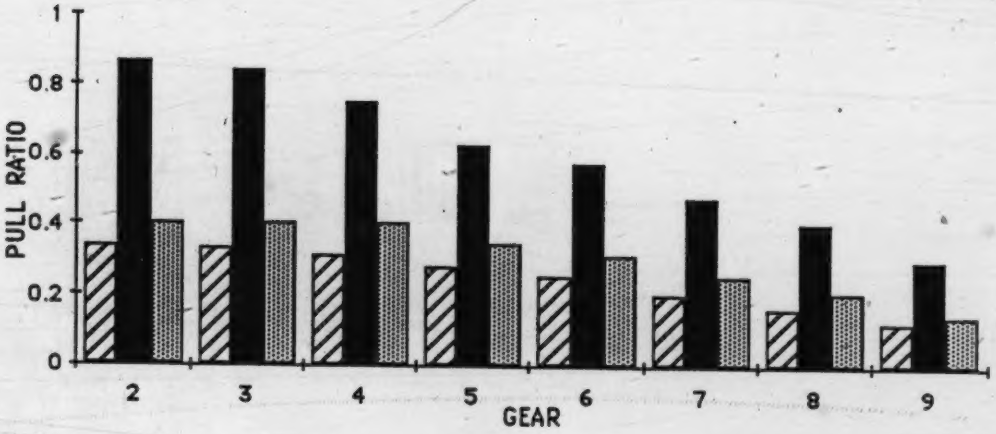


Figure C.98. 4WD/PR/$S_3$/$I_2$

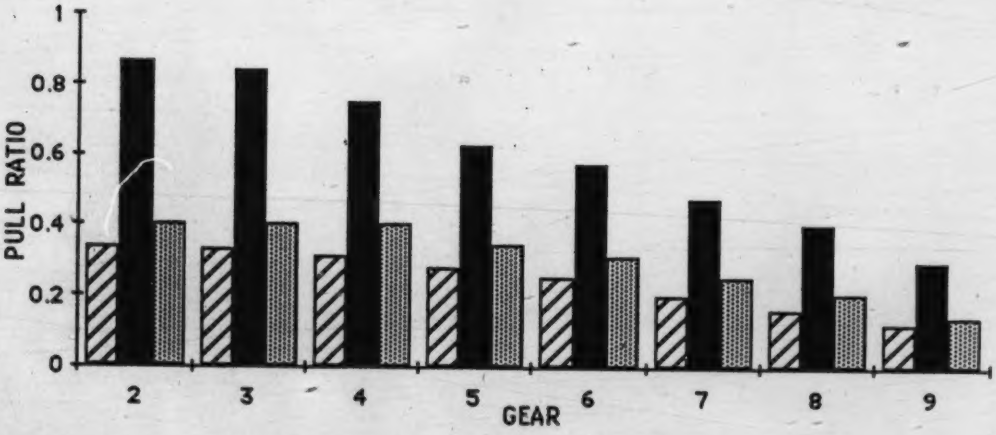


Figure C.99. 4WD/PR/$S_3$/$I_3$

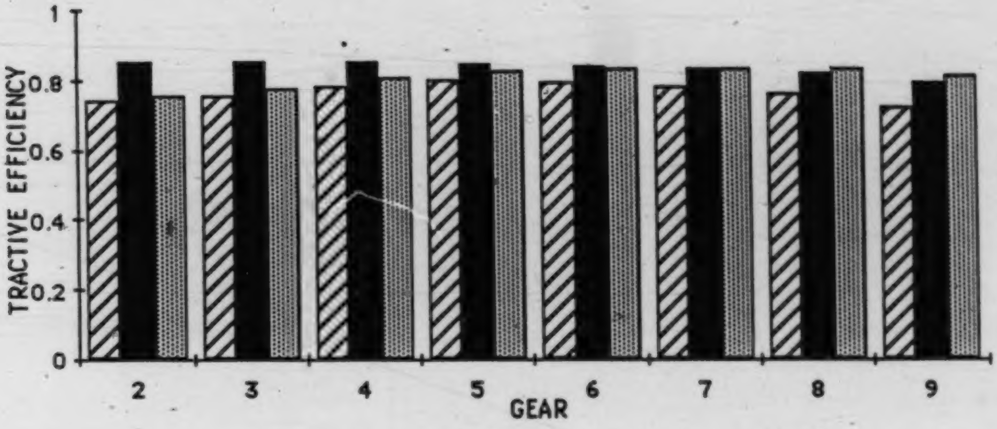


Figure C.100. 4WD/TE/$S_1$/$I_1$

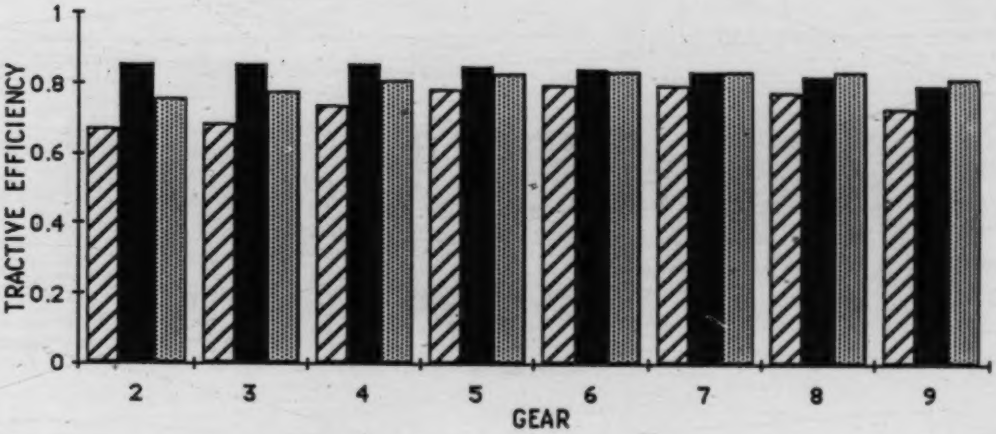


Figure C.101. 4WD/TE/$S_1$/$I_2$

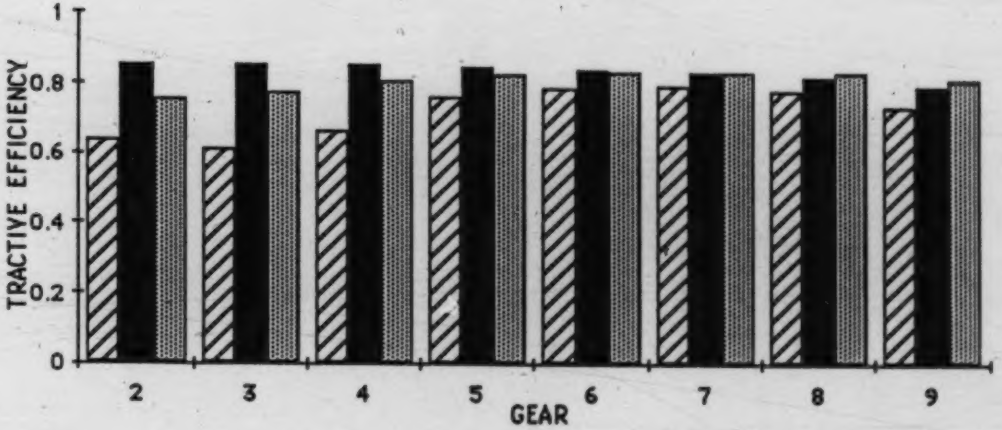


Figure C.102. 4WD/TE/$S_1$/$I_3$

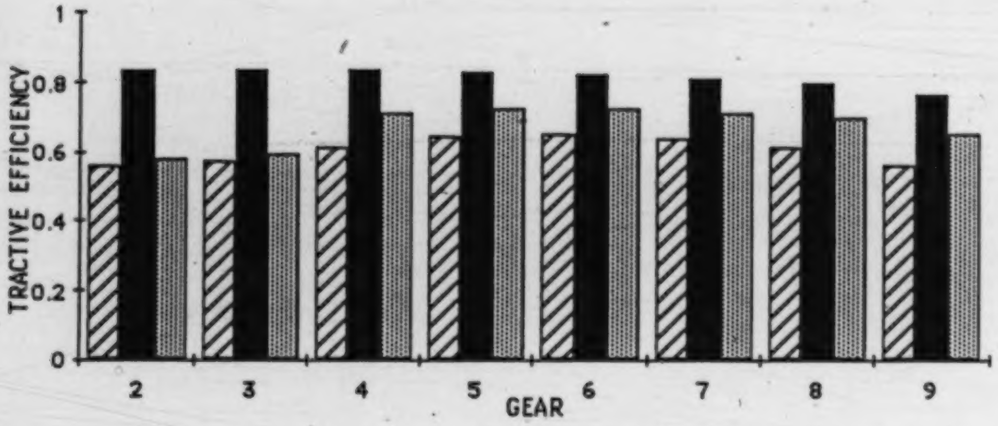


Figure C.103. 4WD/TE/$S_2$/$I_1$

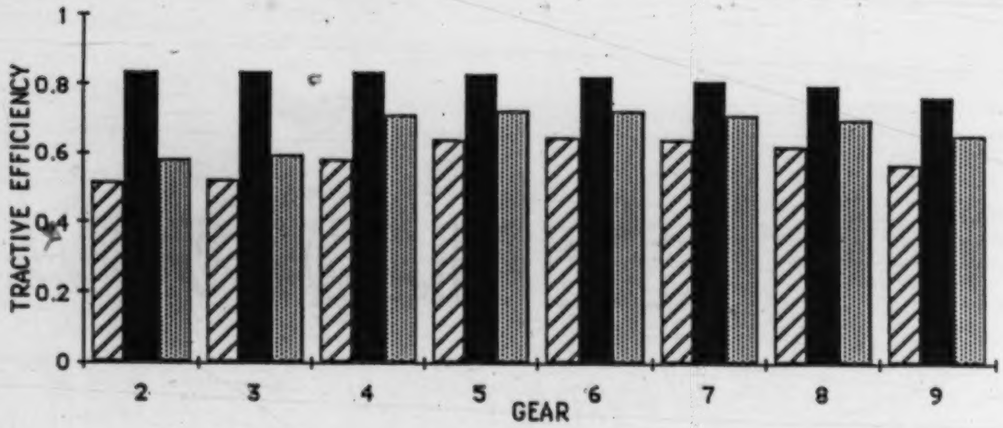


Figure C.104. 4WD/TE/$S_2$/$I_2$

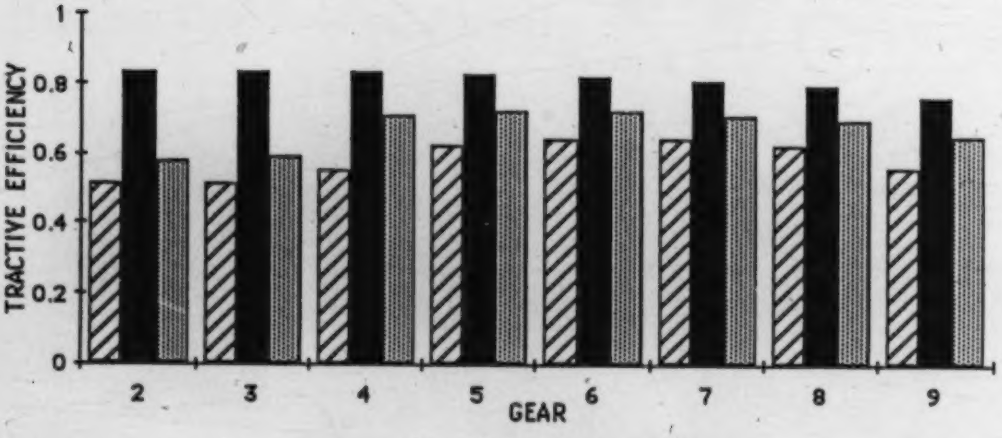


Figure C.105. 4WD/TE/$S_2$/$I_3$

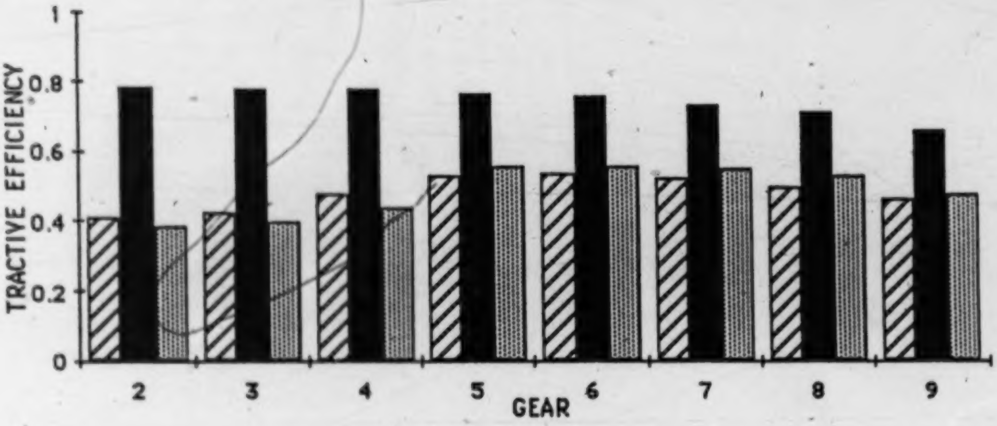


Figure C.106. 4WD/TE/$S_3$/$I_1$

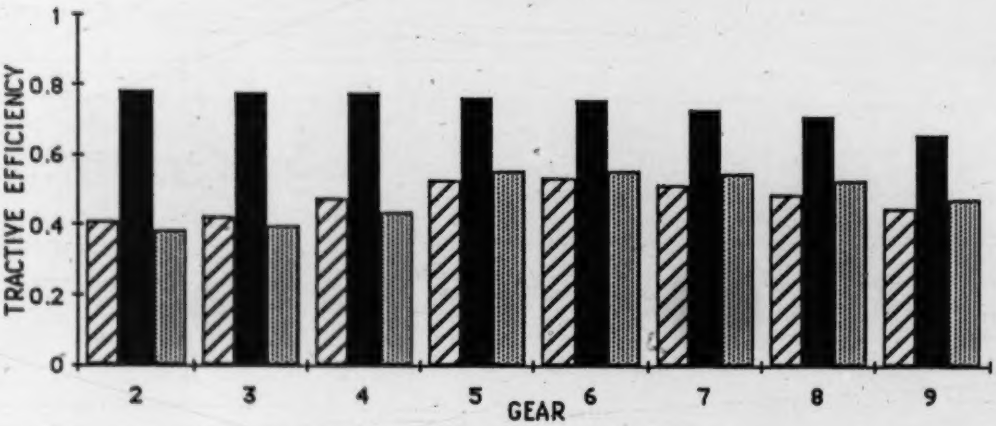


Figure C.107. 4WD/TE/$S_3$/$I_2$

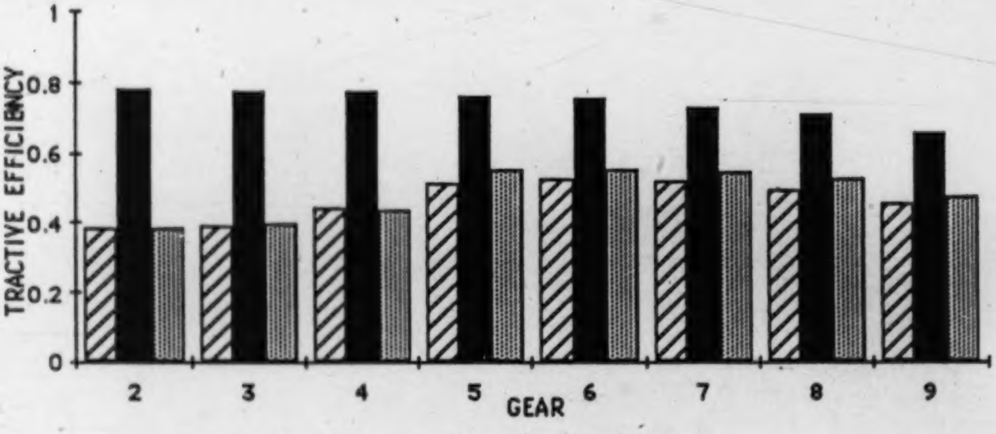


Figure C.108. 4WD/TE/$S_3$/$I_3$

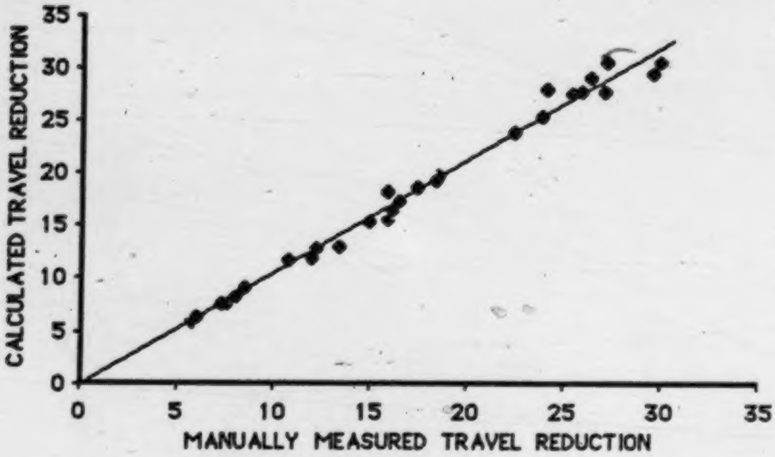


Figure C.109. Calibration curve for Travel Reduction.

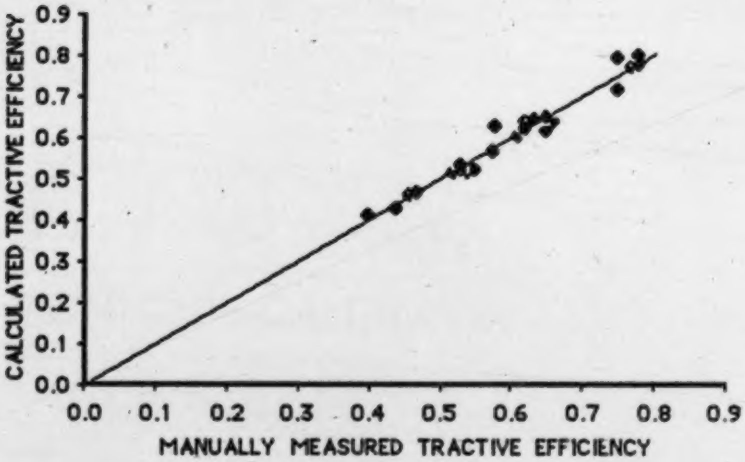


Figure C.110. Calibration curve for Tractive Efficiency.

## APPENDIX D

## PROGRAM LISTING

```
10000 '* The present program was developed by C. Kotzabassis as partial requirement
10010 '*  for his Master of Science degree in Agricultural Engineering.
10020 '*  The program was developed at the University of Alberta, Edmonton, AB
10030 '*  between the years 1984 and 1986.
10040 '*
10050 '* HIGH EFFICIENCY LOCALIZED LOCOMOTOR ANALYSIS/SIMULATION SOFTWARE (HELLAS)
10060 '*
10070 '* INITIALIZATION SECTION
10080 '*
10090 OPTION BASE 1:DEFSTR A-H:DEFINT I-O:KEY OFF:CALL LOGO
10100 '*
10110 '* DIMENSION STATEMENTS
10120 '*
10130 DIM V(20),VA(20),PULL(20),SLIP(20),TRRT(20),TDBPWR(20),TAXPWR(20),THRUST(20)
10140 DIM PTOPWR(20),TORQUE(20),TCWTR(20),TDRWT(20),TDFWT(20),RRTOTL(20),IRPM(20)
10150 DIM TDTR(20),TGTR(20),TFCEFF(20),TEA(20),PWREFF(20),TREFF(20),NGR(20),E(21)
10160 DIM SLP(7),RX(7),R2(9),SE(9),TMAT#(4,4),QMAT#(4,4),RMAT#(4),SMAT#(4)
10170 DIM VMAT#(4,8),INGA(15),RGP(80)
10180 '*
10190 '* FUNCTION DEFINITIONS
10200 '*
10210  DEF FNY1=13+30*(L-1):DEF FNMC(OC,MCM)=MCM*IBMMONO+OC*(1-IBMMONO)
10220 DEF FNALGN(S,J)=RIGHT$(STR$(S),LEN(STR$(S))-1)+SPACE$(J+1-LEN(STR$(S)))
10230 DEF FNOPTR=8+12*(K-2):DEF FNYAX(I)=175-INT((RGP(I)-YMIN)*16/YINC)
10240 DEF FNLPTR=3+L:DEF FNTANPHI(R1,R2,R3,I4,I5)=((R1/2)-R2-.3*SCONV)*I5/(I4*R3)
10250 DEF FNTHEL1=TDRWT(I)*PHI1+.3*SCONV:DEF FNTHEL2=TDFWT(I)*PHI2+.3*SCONV
10260 DEF FNMONY(I)=22-INT(2*(RGP(I)-YMIN)/YINC):DEF FNLSTR(A,B)=INSTR(A,B)
10270 DEF FNTCWTR1=PULL(I)*TDBH/(WHLBS*UCF):DEF FNTRRT=1-(SLIP(I)/100):DEF FNX1=4+2*M
10280 DEF FNTCWTR2=(L1*TORQUE(I)-PULL(I)*(TEA(I)-TDBH)-RRCF*TDFWT(I)*(TEA(I)-TRF)*(L1-1)*UCF)/(WHLBS*UCF)
10290 DEF FNV=VA(I)/TRRT(I):DEF FNPWREFF=TDTR(I)*TRRT(I):DEF FNTAXPWR=THRUST(I)*V(I)/(3.6*L1)
10300 DEF FNPTOPWR=L1*TAXPWR(I)/.96:DEF FNTFCEFF=TDTR(I)/TGTR(I):DEF FNTREFF=TDBPWR(I)/(TAXPWR(I)*L1)
10310 DEF FNTDRWT=SRWT+TCWTR(I):DEF FNTDFWT=STOWT-TDRWT(I):DEF FNQ(I)=J2+I-1
10320 DEF FNRRTOTL=(RRCR*TDRWT(I)+RRCF*TDFWT(I))*UCF:DEF FNTHRUST=PULL(I)+RRTOTL(I)
10330 DEF FNTORQUE=THRUST(I)*TEA(I)/L1:DEF FNWEIGHT=(TDRWT(I)*L2)+(STOWT*(1-L2))
10340 DEF FNTDTR=PULL(I)/(FNWEIGHT*UCF):DEF FNTGTR=THRUST(I)/(FNWEIGHT*UCF)
10350 '*
10360 '* INTERRUPT ASSIGNMENTS ON PF KEYS
10370 '*
10380 KEY 1,"*":ON KEY(1) GOSUB 21090:KEY 2,"*":ON KEY(2) GOSUB 20910
10390 KEY 3,"*":ON KEY(3) GOSUB 21370:KEY 4,"*":ON KEY(4) GOSUB 21120
10400 KEY 5,"*":ON KEY(5) GOSUB 21400:KEY 6,"*":ON KEY(6) GOSUB 20580
10410 KEY 10,"*":ON KEY(10) GOSUB 20110:ON ERROR GOTO 23650
10420 FOR I=7 TO 9:KEY I,"":NEXT:GOSUB 20140:DATA1=":":DATA2="."
10430 FMT1=" ###.###  ":FMT2=" #####.### ":FMT3="   #####    ":FMT4="   ####.### "
10440 FMT5="     ####    ":FMT10="  #.###":FMT11=" ###.##":FMT12="  #####"
10450 '*
10460 '* MAIN PROGRAM
10470 '*
```

```
10480 DEF SEG=0:IF (PEEK(&H410) AND &H30)=&H30 THEN IBMMONO=1 ELSE IBMMONO=0
10490 MKBACK=2:GOSUB 20350:CODE="HELLAS INTEGRATED SOFTWARE":GOSUB 20370:COLOR 15,2:LOCATE 3,20
10500 PRINT "Version 7.00 (C)Copyright 1984 1985 1986":PRINT TAB(22);"C. Kotzabassis. University of Alberta."
10510 CALL KEYBRD:GOSUB 20890:MKBACK=2:GOSUB 20350:CODE="COMPUTER IDENTIFICATION":GOSUB 20370
10520 LOCATE 12,17:COLOR 15,2:DEF SEG=&HF000:ICOUNT=PEEK(&HFFFE)
10530 IF ICOUNT=253 THEN A="PC Junior":GOTO 10580
10540 IF ICOUNT=254 THEN A="XT":GOTO 10580
10550 IF ICOUNT=255 THEN A="PC":GOTO 10580
10560 IF ICOUNT=252 THEN A="AT":GOTO 10580
10570 PRINT "Not an IBM with ";:GOTO 10590
10580 PRINT "IBM ";A;" with ";
10590 DEF SEG=0:IF IBMMONO=1 THEN PRINT "Monochrome/Printer"; ELSE PRINT "Color/Graphics";
10600 PRINT " Display Adapter":PRINT TAB(15);PEEK(&H413)+256*PEEK(&H414);"K of memory;";
10610 PRINT (PEEK(&H410) AND &HC0)/64+1;"disk drive(s) and";
10620 PRINT (PEEK(&H411) AND &HC0)/64;"printer(s).":COLOR 14,FNMC(1,0)
10630 IF RIGHT$(DATE$,4)<"1986" THEN J1=24:J2=13:J3=8 ELSE GOSUB 20890:GOTO 10660
10640 GOSUB 20250:PRINT "Enter date [mm/dd/yy]";:GOSUB 17760:DATE$=ALPHA
10650 GOSUB 20250:PRINT "Enter time [hh:mm:ss]";:GOSUB 17760:TIME$=ALPHA
10660 MENU=1
10670 '*
10680 '* MAIN MENU
10690 '*
10700 MKBACK=2:GOSUB 20350:IDERR=0:IRQ=0:CODE="MAIN  MENU":GOSUB 20370:GOSUB 10780
10710 INGA(1)=1:INGA(2)=4:INGA(3)=20:INGA(4)=2:INGA(5)=25:INGA(6)=15:INGA(7)=14
10720 INGA(8)=2:INGA(15)=0:MENU=0:GOSUB 17890:MENU=INDEX
10730 ON MENU GOTO 20920,10870,12940,15220,19560,15860,18200,21490,10740
10740 GOSUB 20160:BEEP:GOSUB 20250:PRINT "Program is to be terminated.";
10750 GOSUB 20260:PRINT "Verify or Cancel (V/C) ?";
10760 GOSUB 20810:IF A="V" OR A=CHR$(13) THEN COLOR 7,0,0:CLS:DEF SEG=0:POKE 1047,0:END
10770 IF A="C" THEN GOSUB 20140:GOTO 10700 ELSE 10760
10780.COLOR 15,2:RESTORE 10830:FOR I=4 TO 20 STEP 2:READ A:IF IRQ=0 THEN 10800
10790 IF DBASE%=2 AND (I=6 OR I=8 OR I= 14) THEN 10810
10800 LOCATE I,25:PRINT A;
10810 NEXT:RETURN
10820 '* DATA FOR MAIN MENU
10830 DATA" 1.   Display 'H E L P' package "," 2.   Create a new tractor file "," 3.   Edit  an old tractor file "
10840 DATA" 4.   Retrieve a data base file "," 5.   Run  Graphics     package "," 6.   Run  Simulation  package "
10850 DATA" 7.   IBM Serial Communications "," 8.   Run  Utilities    package "," 9.   Terminate program: MS-DOS "
10860 '*
10870 '* CREATE A NEW FILE
10880 '*
10890 IF DBASE%=2 THEN GOSUB 20610:GOTO 10700
10900 FILEOUT="":DD="":ASYST="":EXT1="":DBASE="":MKBACK=2:GOSUB 20350
10910 CODE="CREATE A NEW TRACTOR TEST FILE":GOSUB 20370:GOSUB 11790:GOSUB 11050
10920 GOSUB 12080:GOSUB 20690:RESTORE 12720:FOR I=1 TO 21:READ J1,J2,J3:LOCATE J1,J2
10930 E(I)=SPACE$(J3):IF I=6 THEN E(I)=CTNO
10940 PRINT E(I);:NEXT:GOSUB 20480:GOSUB 20860:GOSUB 12360:GOSUB 20250:GOSUB 20690
10950 KEY(1) OFF:GOSUB 12430:GOSUB 12290:COLOR FNMC(1,7),6:RESTORE 12920:GOSUB 15180
```

```
10960 J3=10:FOR I=1 TO NOBS:COLOR 15,FNMC(6,0):J1=3+I:LOCATE J1,4:PRINT I;:FOR J=0 TO 5
10970 J2=J*12+8:LOCATE J1,J2:GOSUB 20690:PRINT SPACE$(11);:GOSUB 17760
10980 COLOR 15,FNMC(1,0):K1=J+1:GOSUB 11090:LOCATE J1,J2:PRINT USING FMTGP;VAL(ALPHA):NEXT J,I
10990 KEY(1) ON:IDERR=1:COLOR FNMC(6,0):FIN=DD+FILEOUT
11000 GOSUB 20750:IF FILETMP="" THEN 11020 ELSE GOSUB 20260
11010 PRINT "File ";DD;FILEOUT;" exists. Alter filename.";:GOSUB 11050:GOTO 10990
11020 GOSUB 20500:GOSUB 17630:GOSUB 20250:PRINT "Process file ";DD;FILEOUT;" (Y/N)?";
11030 GOSUB 20810:IF A="Y" THEN 11210 ELSE IF A="N" THEN GOSUB 12230 ELSE 11030
11040 GOSUB 13770:CLOSE:GOTO 10890
11050 PTR%=1:GOSUB 20250:PRINT "New file ID [     ]";ASYST;EXT1;:J1=24:J2=14:J3=4:GOSUB 17760:CTNO=ALPHA:PTR%=0:RETURN
11060 '*
11070 '* SUBROUTINE #1
11080 '*
11090 PRMTR=VAL(ALPHA):ON K1 GOTO 11100,11110,11120,11130,11150,11160
11100 TDBPWR(I)=PRMTR:GOTO 11140
11110 PULL(I)=PRMTR:GOTO 11140
11120 VA(I)=PRMTR:GOTO 11140
11130 SLIP(I)=PRMTR
11140 FMTGP=FMT4:RETURN
11150 IRPM(I)=PRMTR:GOTO 11170
11160 NGR(I)=PRMTR
11170 FMTGP=FMT5:RETURN
11180 '*
11190 '* EDIT ENTRANCE POINT
11200 '*
11210 GOSUB 11350
11220 GET #3,1:RSET B1=MKI$(IDERR):PUT #3,1
11230 CLOSE #3:LOCATE 16,1:COLOR 15,2:PRINT "Tractor test report ";:COLOR FNMC(20,0),FNMC(1,7)
11240 PRINT FILEOUT;:COLOR 15,2:PRINT " has been released.":PRINT
11250 PRINT "Defect file flag has been ";:IF IDERR=0 THEN PRINT "cleared" ELSE PRINT "set"
11260 IF MENU=3 THEN GOSUB 20890:GOTO 13440 ELSE GOSUB 20250
11270 PRINT "Would you like to create another record (Y/N)?";:GOSUB 20320
11280 GOSUB 20810:IF A="Y" THEN 10890 ELSE IF A="N" THEN COLOR ,2,2:GOTO 10700
11290 BEEP:GOTO 11280
11300 '* AVAILABLE TIRE FILE NAMES
11310 DATA GOODYEAR,GOODRICH,USER
11320 '*
11330 '* SUBROUTINE #3
11340 '*
11350 RESTORE 11310:N=1:WHILE N<=3:NERR=0:MKBACK=2:GOSUB 20350:CLS:CODE="TRACTOR ANALYSIS"
11360 GOSUB 20370:PRINT:COLOR 15,2:PRINT "Wait! File ";:COLOR FNMC(12,0),FNMC(1,7)
11370 PRINT FILEOUT;:COLOR 15,2:PRINT " is being processed.":READ A
11380 DIRECTORY=A+".DIR":DATAFILE=A+".RND":LOCATE 5,1
11390 OPEN "C:"+DIRECTORY AS #1:OPEN "C:"+DATAFILE AS #2
11400 GOSUB 13710:LOCATE 5,1:COLOR 1:PRINT "Data file ";DATAFILE;" is searched for....."
11410 K1=1:WHILE K1<=2:PRINT:COLOR 14:ON K1 GOTO 11420,11430
11420 PRINT "front tire size ";DFRONT;":";IFPLY;"...";:GOTO 11440
11430 COLOR 14:PRINT "rear  tire size ";DREAR;":";IRPLY;"...";
```

```
11440 GET #1,1:MARK=CVI(BOUND):L=2:WHILE NOT EOF(1):GET#1,L:L=L+1
11450 JCOUNT=CVI(CNT):CLASS=CL:CODE=CD:IPLY=CVI(APR):ON K1 GOTO 11460,11470
11460 IF CODE=DFRONT AND IPLY=IFPLY THEN 11500 ELSE 11480
11470 IF CODE=DREAR AND IPLY=IRPLY THEN 11500
11480 WEND:IF N<3 THEN 11540 ELSE LOCATE 12,1:PRINT "Fatal Error in calculations.";:CLOSE #1,#2:
11490 GOSUB 12230:IDERR=1:GOTO 11720
11500 GET #2,JCOUNT:ON K1 GOTO 11510,11520
11510 TRF=CVS(ATR):LDF=CVI(ATL):IPF=CVI(ATI):TWF=CVS(ATW):TDF=CVS(ATD):GOTO 11530
11520 TRR=CVS(ATR):LDR=CVI(ATL):IPR=CVI(ATI):TWR=CVS(ATW):TDR=CVS(ATD):N=4
11530 K1=K1+1:COLOR 31:PRINT "OK":WEND
11540 CLOSE #1,#2:N=N+1:WEND:IF UNIT%=1 THEN GOSUB 11690
11550 IF MENU=6 THEN RETURN
11560 '*
11570 '* TRACTOR ANALYSIS ON CONCRETE
11580 '*
11590 COLOR 15:LOCATE 12,1:PRINT "Tractor analysis is in progress.....";:GOSUB 11680:GOSUB 17290:GOSUB 17160
11600 FOR I=1 TO NOBS:TCWTR(I)=FNTCWTR1:GOSUB 11660:TCWTR(I)=FNTCWTR2:GOSUB 11660
11610 TDTR(I)=FNTDTR:TGTR(I)=FNTGTR:TRRT(I)=FNTRRT:V(I)=FNV:PWREFF(I)=FNPWREFF
11620 TAXPWR(I)=FNTAXPWR:PTOPWR(I)=FNPTOPWR:TFCEFF(I)=FNTFCEFF:TREFF(I)=FNTREFF:NEXT
11630 IF TRAC%<3 THEN PLDF=SFWT*IPF*100/(NUMF*LDF*PF):PLDR=SRWT*IPR*100/(NUMR*LDR*PR):GOTO 11710
11640 PRMTR=(IPF/(LDF*PF)+IPR/(LDR*PR))*50:LMG=(NUMF+NUMR)/2
11650 PLDF=SFWT*PRMTR/(LMG-(LMG MOD 2)):PLDR=SRWT*PRMTR/(LMG+(LMG MOD 2)):GOTO 11710
11660 TDRWT(I)=FNTDRWT:TDFWT(I)=FNTDFWT:RRTOTL(I)=FNRRTOTL:THRUST(I)=FNTHRUST
11670 GOSUB 17140:TORQUE(I)=FNTORQUE:RETURN
11680 PHI1=FNTANPHI(TDR,TRR,PR,LDR,IPR):PHI2=FNTANPHI(TDF,TRF,PF,LDF,IPF):RETURN
11690 TRF=TRF/39.37:LDF=LDF/2.2:IPF=(IPF/.145)+.5:TWF=TWF/39.37:TDF=TDF/39.37
11700 TRR=TRR/39.37:LDR=LDR/2.2:IPR=(IPR/.145)+.5:TWR=TWR/39.37:TDR=TDR/39.37:RETURN
11710 COLOR FNMC(15,0),FNMC(1,7):PRINT "Analysis terminated.":COLOR FNMC(15,7),2
11720 GOSUB 13770:RETURN
11730 '* UNIT SYSTEM DEPENDENT CONSTANTS
11740 DATA "METR","KW","SIU",0.00981,0.0254
11750 DATA "ENGL","HP","IMP",1,1
11760 '*
11770 '* SUBROUTINE #7
11780 '*
11790 INGA(11)=5:INGA(12)=11:INGA(13)=31:INGA(14)=46:GOSUB 20630:RESTORE 12040
11800 LOCATE 7,34:COLOR 1,2:PRINT "NO-FILE MENU":J1=9:J2=11:J3=34:GOSUB 20400
11810 INGA(1)=2:INGA(2)=9:INGA(3)=11:INGA(4)=2:INGA(5)=34:INGA(6)=15:INGA(7)=14
11820 INGA(8)=2:INGA(15)=0:GOSUB 17890:IF INDEX=1 THEN DD="A:" ELSE DD="B:"
11830 LMG=1:GOSUB 11930:CODE=MID$(DBASE,5,4):CLASS=LEFT$(DBASE,3)
11840 IF CODE="METR" THEN UNIT%=1 ELSE IF CODE="ENGL" THEN  UNIT%=2 ELSE 11880
11850 IF CLASS="ORD" THEN DBASE%=1 ELSE IF CLASS="SIM" THEN DBASE%=2 ELSE 11880
11860 GOSUB 12010:TRAC%=1:EXT1=MID$(DBASE,9,4):RESTORE 12030:WHILE TRAC%<5:READ A
11870 IF EXT1=A THEN RETURN ELSE TRAC%=TRAC%+1:WEND
11880 GOSUB 20610:GOTO 11790
11890 '*
11900 '* CHECK DATABASE
11910 '*
```

```
11920 LMG=0:FIN=DD+DBASE:GOSUB 20760:IF FILETMP="" THEN 11930 ELSE 11980
11930 FIN=DD+"???_*.*":GOSUB 20760:IF FILETMP="" THEN 11940 ELSE 11970
11940 GOSUB 20240:PRINT "Database error. Initialize a database (Y/N)?";
11950 GOSUB 20810:IF A="Y" THEN GOSUB 20560 ELSE IF A="N" THEN 11970 ELSE 11950
11960 RSET FMARK=MKI$(0):PUT #2,1:CLOSE #2:GOTO 11920
11970 IF LMG=0 THEN GOSUB 20610:GOTO 11920
11980 IF INSTR(FIN,"?")>0 OR INSTR(FIN,"*")>0 THEN DBASE=RIGHT$(FILETMP,12)
11990 GOSUB 20260:PRINT "Volume # ";DD;" \ ";DBASE;
12000 RETURN
12010 IF UNIT%=1 THEN RESTORE 11740 ELSE RESTORE 11750
12020 READ ASYST,APL,EXT2,UCF,SCONV:RETURN
12030 DATA ".2WD",".FW2",".FW4",".4WD"
12040 DATA " A: (left)  "," B: (right) "
12050 '*
12060 '* SUBROUTINE #8
12070 '*
12080 COLOR ,6,6:CLS:CODE="TRACTOR DESIGN PARAMETERS":GOSUB 20370:COLOR FNMC(1,15),6:LOCATE 3,1
12090 RESTORE 12150:FOR I=1 TO 21:READ J1,J2,A:IF I=9 OR I=13 THEN GOSUB 12120
12100 LOCATE J1,J2:PRINT A;:IF I=4 THEN PRINT APL;
12110 NEXT:COLOR 15,FNMC(6,0):RETURN
12120 IF TRAC%=4 THEN READ A ELSE READ B
12130 RETURN
12140 '* DATA FOR TRACTOR INFORMATION MENU
12150 DATA 3,1,"JOB #",3,12,"# OBSERV",3,24,"TRACTOR NAME",3,64,"RATED "
12160 DATA 5,1,"LOCATION",5,23,"TEST #",5,35,"DATE",5,57,"SURFACE"
12170 DATA 7,1,"FRONT SIZE","INNER TIRE",7,21,"PLY",7,28,"PRS",7,36,"F#"
12180 DATA 7,41,"REAR SIZE","OUTER TIRE",7,61,"PLY",7,68,"PRS",7,76,"R#"
12190 DATA 9,1,"FRONT WT",9,17,"TOTAL WT",9,32,"DB HEIGHT",9,49,"WH BASE",9,64,"RAT ENG RPM"
12200 '*
12210 '* SUBROUTINE #9
12220 '*
12230 FOR I=1 TO 20:V(I)=0:TRRT(I)=0:TAXPWR(I)=0:PTOPWR(I)=0:THRUST(I)=0
12240 TORQUE(I)=0:TCWTR(I)=0:TDRWT(I)=0:TDFWT(I)=0:TDTR(I)=0:TGTR(I)=0
12250 RRTOTL(I)=0:TEA(I)=0:TFCEFF(I)=0:PWREFF(I)=0:TREFF(I)=0:NEXT:RETURN
12260 '*
12270 '* SUBROUTINE #10
12280 '*
12290 JOBN=VAL(E(1)):NOBS=VAL(E(2)):DESIGN=E(3):RATPWR=VAL(E(4)):ALOC=E(5):CTND=E(6):DATE=E(7):FSURF=E(8)
12300 DFRONT=E(9):IFPLY=VAL(E(10)):PF=VAL(E(11)):NUMF=VAL(E(12)):DREAR=E(13):IRPLY=VAL(E(14)):PR=VAL(E(15))
12310 NUMR=VAL(E(16)):SFWT=VAL(E(17)):STOWT=VAL(E(18)):TDBH=VAL(E(19)):WHLBS=VAL(E(20)):OPRPM=VAL(E(21))
12320 RETURN
12330 '*
12340 '* SUBROUTINE #11
12350 '*
12360 ICOUNT=0:GOSUB 20260:PRINT "BS,";CHR$(27);":delete  SP,";CHR$(26);":insert  ";
12370 PRINT CHR$(26);"?,";CHR$(17);"?:field forward  ?";CHR$(27);":field reverse  ESC:terminate";
12380 IF MENU=3 THEN GOSUB 12670
12390 GOSUB 20690:RETURN
```

```
12400 '*
12410 '* SUBROUTINE #12
12420 '*
12430 PTR%=2:DUMMY=CHR$(254):LOCATE 3,1:MKBACK=6:GOSUB 20740
12440 RESTORE 12720:GOSUB 20690:L=1
12450 LMG=1:READ J1,J2,J3:GOSUB 12690
12460 GOSUB 20810:GOSUB 20690:ON LEN(A) GOTO 12470,12520
12470 IF A=CHR$(13) OR A=CHR$(9) THEN 12550 ELSE IF A=CHR$(8) THEN 12570
12480 IF ASC(A)>31 AND ASC(A)<125 THEN 12580
12490 IF A=CHR$(27) THEN COLOR ,FNMC(4,0) ELSE 12540
12500 GOSUB 20250:PRINT "Editing is to be aborted. Verify (Y/N)?";
12510 GOSUB 20810:IF A="Y" THEN RETURN 10700 ELSE IF A="N" THEN GOSUB 20250:GOTO 12460 ELSE 12510
12520 A=RIGHT$(A,1):IF A=CHR$(15) THEN 12640 ELSE IF A=CHR$(75) THEN 12590
12530 IF A=CHR$(77) THEN 12610 ELSE IF A=CHR$(79) AND ICOUNT>0 THEN GOSUB 12680:COLOR ,FNMC(6,0):GOSUB 20260:PTR%=0:RETURN
12540 BEEP:GOTO 12460
12550 GOSUB 12680:L=L+1:IF L=22 THEN GOSUB 12670:GOTO 12440 ELSE IF L=6 THEN READ J1,J2,J3:L=L+1
12560 GOTO 12450
12570 IF LMG=1 THEN 12540 ELSE A=" ":GOSUB 12700:GOTO 12600
12580 IF LMG>J3 THEN 12540 ELSE GOSUB 12700:GOTO 12620
12590 IF LMG=1 THEN 12540 ELSE GOSUB 12680
12600 LMG=LMG-1:GOSUB 12690:GOTO 12460
12610 IF LMG>J3 THEN 12540 ELSE GOSUB 12680
12620 LMG=LMG+1:IF LMG<=J3 THEN GOSUB 12690
12630 GOTO 12460
12640 IF L=1 THEN 12540 ELSE GOSUB 12680
12650 L=L-1:IF L=6 THEN L=L-1
12660 RESTORE 12720:FOR I=1 TO L-1:READ J1,J2,J3:NEXT:GOTO 12450
12670 ICOUNT=1:LOCATE 25,66:PRINT "END:terminate";:RETURN
12680 ALPHA=MID$(E(L),LMG,1):SWAP DUMMY,ALPHA:GOSUB 12690:SWAP DUMMY,ALPHA:RETURN
12690 LOCATE J1,FNQ(LMG):PRINT DUMMY;:RETURN
12700 MID$(E(L),LMG,1)=A:LOCATE J1,FNQ(LMG):PRINT A;:RETURN
12710 '* DATA FOR TRACTOR INFORMATION MENU FIELDS (LINE, COLUMN, LENGTH)
12720 DATA 3,6,4,3,20,2,3,36,26,3,72,7,5,9,12,5,29,4,5,39,16,5,64,15,7,11,8,7,24,2
12730 DATA 7,31,3,7,38,1,7,51,8,7,64,2,7,71,3,7,78,1,9,9,5,9,25,5,9,41,6,9,56,6,9,75,4
12740 '*
12750 '* SUBROUTINE #13
12760 '*
12770 CLOSE:GOSUB 20860:GOSUB 20240:IF DBASE="" THEN 12850
12780 IF FILEOUT="" THEN 12860
12790 PTR%=3:PRINT "Process file ";DD;FILEOUT;" [Y/N/ALT-1...9]";:LOCATE 25,1
12800 PRINT "Y=Yes   N=No   ESC=Main Menu   ALT-1...9=Change Task";
12810 GOSUB 20810:ON LEN(A) GOTO 12820,12910
12820 IF A=CHR$(27) THEN COLOR ,,2:PTR%=0:RETURN 10700 ELSE IF A="Y" THEN PTR%=0:RETURN
12830 IF A="N" THEN GOSUB 20240:GOTO 12860
12840 BEEP:GOTO 12810
12850 GOSUB 20300:GOSUB 11790:IF MENU=0 THEN RETURN
12860 IF DBASE%=2 AND (MENU=2 OR MENU=3 OR MENU=6) THEN GOSUB 20250 ELSE 12880
12870 PRINT "Invalid routine for database. Examine <F3> or <F5>";:GOTO 12810
```

```
12880 GOSUB 13480
12890 IF DBASE%=1 THEN MODEL=0 ELSE GOSUB 20300:GOSUB 15990:GOSUB 20480
12900 GOTO 12770
12910 MENU=ASC(RIGHT$(A,1))-119:IF MENU<1 OR MENU>9 THEN 12840 ELSE RETURN 10730
12920 DATA "    #         POWER         PULL         SPEED        SLIP       RPM          GEAR   "
12930 '*
12940 '* EDIT AN EXISTING FILE
12950 '*
12960 IF DBASE%=2 THEN GOSUB 20610:GOTO 10700 ELSE N=1:IDERR=0
12970 MKBACK=2:GOSUB 20350:CODE="EDIT AN EXISTING FILE":GOSUB 20370
12980 GOSUB 12230
12990 GOSUB 12770
13000 GOSUB 14330
13010 GOSUB 12080
13020 RESTORE 12720:GOSUB 20690:FOR I=1 TO 21:READ J1,J2,J3
13030 LOCATE J1,J2:PRINT E(I):NEXT:GOSUB 20260:COLOR ,FNMC(6,0)
13040 PRINT "Home: Edit   End: Process  PgUp/Dn: 2nd Page   ESC: Escape editing";
13050 GOSUB 20810:ON LEN(A) GOTO 13060,13070
13060 IF A=CHR$(27) THEN CLOSE:GOSUB 20200:GOTO 12970 ELSE 13090
13070 A=RIGHT$(A,1):IF A=CHR$(79) THEN 13420 ELSE IF A=CHR$(71) THEN 13100
13080 IF A=CHR$(73) OR A=CHR$(81) THEN 13120
13090 BEEP:GOTO 13050
13100 IDERR=1:GOSUB 20200:GOSUB 12360:GOSUB 12430
13110 GOSUB 12290:GOTO 13040
13120 GOSUB 20180:RESTORE 12920:GOSUB 15180
13130 FOR I=1 TO NOBS:LOCATE 3+I,4:PRINT I;TAB(8); 'COLOR FNMC(15,7),FNMC(6,0):
13140 PRINT USING FMT4;TDBPWR(I);PULL(I);VA(I);SLIP(I);
13150 PRINT USING FMT5;IRPM(I);NGR(I);:NEXT
13160 ON KEY(11) GOSUB 13290:ON KEY(12) GOSUB 13310:ON KEY(13) GOSUB 13330
13170 ON KEY(14) GOSUB 13300:GOSUB 20180:L=1:K=2:GOSUB 20250:COLOR ,FNMC(6,0)
13180 PRINT "Home: Edit  End: Process  PgUp/Dn: 1st Page  Arrows: Select  ESC: Escape";
13190 GOSUB 13340
13200 GOSUB 20330:MKBACK=6:GOSUB 20740
13210 '*
13220 '* SELECT ENTRY FOR EDITING
13230 '*
13240 GOSUB 20810:ON LEN(A) GOTO 13250,13260
13250 IF A=CHR$(27) THEN CLOSE:GOSUB 20200:GOTO 12970 ELSE 13280
13260 A=RIGHT$(A,1):IF A=CHR$(71) THEN 13370 ELSE IF A=CHR$(79) THEN 13420
13270 IF A=CHR$(73) OR A=CHR$(81) THEN 13010
13280 BEEP:GOTO 13240
13290 IF L>1 THEN GOSUB 13360:L=L-1:GOTO 13340 ELSE 13280
13300 IF L<NOBS THEN GOSUB 13360:L=L+1:GOTO 13340 ELSE 13280
13310 IF K>2 THEN GOSUB 13360:K=K-1 ELSE IF L>1 THEN GOSUB 13360:K=7:L=L-1 ELSE 13280
13320 GOTO 13340
13330 IF K<7 THEN GOSUB 13360:K=K+1 ELSE IF L<NOBS THEN GOSUB 13360:K=2:L=L+1 ELSE 13280
13340 LOCATE FNLPTR,FNOPTR:COLOR 18:PRINT CHR$(26):COLOR 15
13350 LOCATE FNLPTR,FNOPTR:GOSUB 20180:RETURN 13200
```

```
13360 LOCATE FNLPTR,FNOPTR:COLOR FNMC(6,0),FNMC(6,0):PRINT " ":RETURN
13370 LOCATE FNLPTR,FNOPTR:COLOR FNMC(6,0),FNMC(2,7)
13380 GOSUB 20180:PRINT SPACE$(11);:J1=FNLPTR:J2=FNOPTR:J3=11
13390 LOCATE J1,J2:GOSUB 17760:K1=K-1:I=L:GOSUB 11090
13400 LOCATE FNLPTR,FNOPTR:COLOR 14,6
13410 PRINT USING FMTGP;PRMTR;:GOSUB 13340
13420 GOSUB 20200:IDERR=0:GOTO 11210
13430 GOSUB 12230:GOSUB 13770:GOSUB 20260:PRINT "Changes have been saved.";:CLOSE #3:GOSUB 20890
13440 COLOR FNMC(15,7),2,2:GOTO 12970
13450 '*
13460 '* SUBROUTINE #14
13470 '*
13480 GOSUB 20250:PRINT "Define the ID of the file to be processed [     ]";
13490 LOCATE 24,44:PRINT CTNO;:PTR%=4:J1=24:J2=44:J3=4:GOSUB 17760
13500 IF ASC(ALPHA)=27 THEN GOSUB 20260:GOTO 13480 ELSE IF ASC(ALPHA)=13 THEN 13520
13510 IF LEN(ALPHA)<4  THEN GOSUB 20260:GOTO 13480 ELSE CTNO=ALPHA
13520 GOSUB 20480:GOSUB 20250:PTR%=0:RETURN
13530 '*
13540 '* TRACTOR FILE FIELDS
13550 '*
13560 FIELD #3,4 AS A1,2 AS B1,2 AS C1,2 AS D1,2 AS E1,2 AS F1,4 AS G1,2 AS H1
13570 FIELD #3,2 AS A2,26 AS B2,12 AS C2,3 AS D2,2 AS E2,16 AS F2,15 AS G2
13580 FIELD #3,8 AS A3,2 AS B3,2 AS C3,4 AS D3,8 AS E3,2 AS F3,2 AS G3,4 AS H3
13590 FIELD #3,4 AS A4,4 AS B4,4 AS C4,4 AS D4,2 AS E4,4 AS F4,4 AS G4,4 AS H4
13600 FIELD #3,4 AS A5,4 AS B5,4 AS C5,4 AS D5,4 AS E5
13610 FIELD #3,2 AS A6,2 AS B6,4 AS C6,4 AS D6,2 AS E6,2 AS F6,4 AS G6,4 AS H6
13620 FIELD #3,2 AS A7,2 AS B7,2 AS C7,2 AS D7,2 AS E7,2 AS F7,2 AS G7
13630 FIELD #3,4 AS A8,4 AS B8,4 AS C8,4 AS D8,4 AS E8,4 AS F8,4 AS G8
13640 FIELD #3,2 AS A9,4 AS B9,4 AS C9,4 AS D9,4 AS E9,2 AS F9
13650 FIELD #3,4 AS A10,4 AS B10,4 AS C10,4 AS D10,4 AS E10,4 AS F10,4 AS G10,4 AS H10
13660 FIELD #3,4 AS A11,4 AS B11,4 AS C11,4 AS D11,4 AS E11,4 AS F11,4 AS G11,4 AS H11
13670 RETURN
13680 '*
13690 '* TIREFILE FIELDS
13700 '*
13710 FIELD #1,2 AS BOUND:FIELD #1,2 AS CNT,1 AS CL,8 AS CD,2 AS APR
13720 FIELD #2,4 AS ATR,2 AS ATL,2 AS ATI,4 AS ATW,4 AS ATD,5 AS DUMMY
13730 RETURN
13740 '*
13750 '* SUBROUTINE #5 - SUPERVISOR - PUT
13760 '*
13770 GOSUB 13850:GOSUB 13970:GOSUB 14040
13780 K=10:GOSUB 14150
13790 K=K+NOBS:GOSUB 14210
13800 K=K+NOBS:GOSUB 14270
13810 RETURN
13820 '*
13830 '* SUBROUTINE #5/A
```

```
13840 '*
13850 SRWT=STOWT-SFWT:TCGDST=SFWT*WHLBS/STOWT:GOSUB 13560
13860 LSET A1=CTNO:RSET B1=MKI$(IDERR):RSET C1=MKI$(UNIT%):RSET D1=MKI$(MODEL)
13870 RSET E1=MKI$(LAND):RSET F1=MKI$(IMPL):RSET G1=MKS$(VCNIX):RSET H1=MKI$(LAB):PUT #3,1
13880 RSET A2=MKI$(NOBS):LSET B2=DESIGN:LSET C2=ALOC:LSET D2=APL
13890 RSET E2=MKI$(JOBN):LSET F2=DATE:LSET G2=FSURF:PUT #3,2
13900 RSET A3=DFRONT:RSET B3=MKI$(NUMF):RSET C3=MKI$(IFPLY):RSET D3=MKS$(PF)
13910 RSET E3=DREAR:RSET F3=MKI$(NUMR):RSET G3=MKI$(IRPLY):RSET H3=MKS$(PR):PUT #3,3
13920 RSET A4=MKS$(RATPWR):RSET B4=MKS$(SFWT):RSET C4=MKS$(SRWT):RSET D4=MKS$(STOWT)
13930 RSET E4=MKI$(OPRPM):RSET F4=MKS$(TDBH):RSET G4=MKS$(WHLBS):RSET H4=MKS$(TCGDST):PUT #3,4:RETURN
13940 '*
13950 '* SUBROUTINE #5/B
13960 '*
13970 RSET A5=MKS$(TRF):RSET B5=MKS$(TRR):RSET C5=MKS$(RRC):RSET D5=MKS$(PLDF)
13980 RSET E5=MKS$(PLDR):PUT #3,5:RSET A6=MKI$(LDF):RSET B6=MKI$(IPF)
13990 RSET C6=MKS$(TWF):RSET D6=MKS$(TDF):RSET E6=MKI$(LDR):RSET F6=MKI$(IPR)
14000 RSET G6=MKS$(TWR):RSET H6=MKS$(TDR):PUT #3,6:RETURN
14010 '*
14020 '* SUBROUTINE #5/C
14030 '*
14040 RSET A7=MKI$(INGA(1)):RSET B7=MKI$(INGA(2)):RSET C7=MKI$(INGA(3)):RSET D7=MKI$(INGA(4))
14050 RSET E7=MKI$(INGA(5)):RSET F7=MKI$(INGA(6)):RSET G7=MKI$(INGA(7)):PUT #3,7
14060 RSET A7=MKI$(INGA(8)):RSET B7=MKI$(INGA(9)):RSET C7=MKI$(INGA(10)):RSET D7=MKI$(INGA(11))
14070 RSET E7=MKI$(INGA(12)):RSET F7=MKI$(INGA(13)):RSET G7=MKI$(INGA(14)):PUT #3,8
14080 RSET A8=MKS$(RGP(41)):RSET B8=MKS$(RGP(42)):RSET C8=MKS$(RGP(43)):RSET D8=MKS$(RGP(44))
14090 RSET E8=MKS$(RGP(45)):RSET F8=MKS$(RGP(46)):RSET G8=MKS$(RGP(47)):PUT #3,9
14100 RSET A8=MKS$(RGP(48)):RSET B8=MKS$(RGP(49)):RSET C8=MKS$(RGP(50)):RSET D8=MKS$(RGP(51))
14110 RSET E8=MKS$(RGP(52)):RSET F8=MKS$(RGP(53)):RSET G8=MKS$(RGP(54)):PUT #3,10:RETURN
14120 '*
14130 '* SUBROUTINE #5/D
14140 '*
14150 FOR I=1 TO NOBS:RSET A9=MKI$(NGR(I)):RSET B9=MKS$(TDBPWR(I))
14160 RSET C9=MKS$(PULL(I)):RSET D9=MKS$(SLIP(I)):RSET E9=MKS$(VA(I))
14170 RSET F9=MKI$(IRPM(I)):PUT #3,K+I:NEXT:RETURN
14180 '*
14190 '* SUBROUTINE #5/E
14200 '*
14210 FOR I=1 TO NOBS:RSET A10=MKS$(PTOPWR(I)):RSET B10=MKS$(TAXPWR(I))
14220 RSET C10=MKS$(TORQUE(I)):RSET D10=MKS$(TCWTR(I)):RSET E10=MKS$(TRRT(I))
14230 RSET F10=MKS$(TDTR(I)):RSET G10=MKS$(TGTR(I)):RSET H10=MKS$(THRUST(I)):PUT #3,K+I:NEXT:RETURN
14240 '*
14250 '* SUBROUTINE #5/F
14260 '*
14270 FOR I=1 TO NOBS:RSET A11=MKS$(TFCEFF(I)):RSET B11=MKS$(PWREFF(I))
14280 RSET C11=MKS$(TREFF(I)):RSET D11=MKS$(TDFWT(I)):RSET E11=MKS$(TDRWT(I))
14290 RSET F11=MKS$(RRTOTL(I)):RSET G11=MKS$(V(I)):RSET H11=MKS$(TEA(I)):PUT #3,K+I:NEXT:RETURN
14300 '*
14310 '* SUBROUTINE #15 - SUPERVISOR - GET
```

```
14320 '*
14330 GOSUB 14410:GOSUB 14560
14340 K=10:GOSUB 14670
14350 K=K+NOBS:GOSUB 14720
14360 K=K+NOBS:GOSUB 14770
14370 RETURN
14380 '*
14390 '* SUBROUTINE #15/A
14400 '*
14410 GOSUB 20500
14420 GET #3,1:CTNO=A1:IDERR=CVI(B1):UNIT%=CVI(C1):MODEL=CVI(D1):LAND=CVI(E1):IMPL=CVI(F1):VCNIX=CVS(G1):LAB=CVI(H1)
14430 GET #3,2:NOBS=CVI(A2):DESIGN=B2:ALOC=C2:APL=D2:JOBN=CVI(E2):DATE=F2:FSURF=G2
14440 GET #3,3:DFRONT=A3:NUMF=CVI(B3):IFPLY=CVI(C3):PF=CVS(D3):DREAR=E3:NUMR=CVI(F3):IRPLY=CVI(G3):PR=CVS(H3)
14450 GET #3,4:RATPWR=CVS(A4):SFWT=CVS(B4):SRWT=CVS(C4):STOWT=CVS(D4):OPRPM=CVI(E4):TDBH=CVS(F4):WHLBS=CVS(G4)
14460 TCGDST=CVS(H4):E(1)=FNALGN(JOBN,4):E(2)=FNALGN(NOBS,2):E(3)=DESIGN:E(4)=FNALGN(RATPWR,7):E(5)=ALOC
14470 E(6)=CTNO:E(7)=DATE:E(8)=FSURF:E(9)=DFRONT:E(10)=FNALGN(IFPLY,2):E(11)=FNALGN(PF,3):E(12)=FNALGN(NUMF,1)
14480 E(13)=DREAR:E(14)=FNALGN(IRPLY,2):E(15)=FNALGN(PR,3):E(16)=FNALGN(NUMR,1):E(17)=FNALGN(SFWT,4)
14490 E(18)=FNALGN(STOWT,5):E(19)=FNALGN(TDBH,6):E(20)=FNALGN(WHLBS,6):E(21)=FNALGN(OPRPM,4)
14500 GET #3,5:TRF=CVS(A5):TRR=CVS(B5):RRC=CVS(C5):PLDF=CVS(D5):PLDR=CVS(E5)
14510 GET #3,6:LDF=CVI(A6):IPF=CVI(B6):TWF=CVS(C6):TDF=CVS(D6):LDR=CVI(E6)
14520 IPR=CVI(F6):TWR=CVS(G6):TDF=CVS(H6):RETURN
14530 '*
14540 '* SUBROUTINE #15/A1
14550 '*
14560 GET #3,7:INGA(1)=CVI(A7):INGA(2)=CVI(B7):INGA(3)=CVI(C7)
14570 INGA(4)=CVI(D7):INGA(5)=CVI(E7):INGA(6)=CVI(F7):INGA(7)=CVI(G7)
14580 GET #3,8:INGA(8)=CVI(A7):INGA(9)=CVI(B7):INGA(10)=CVI(C7)
14590 INGA(11)=CVI(D7):INGA(12)=CVI(E7):INGA(13)=CVI(F7):INGA(14)=CVI(G7)
14600 GET #3,9:RGP(41)=CVS(A8):RGP(42)=CVS(B8):RGP(43)=CVS(C8)
14610 RGP(44)=CVS(D8):RGP(45)=CVS(E8):RGP(46)=CVS(F8):RGP(47)=CVS(G8)
14620 GET #3,10:RGP(48)=CVS(A8):RGP(49)=CVS(B8):RGP(50)=CVS(C8)
14630 RGP(51)=CVS(D8):RGP(52)=CVS(E8):RGP(53)=CVS(F8):RGP(54)=CVS(G8):RETURN
14640 '*
14650 '* SUBROUTINE #15/B
14660 '*
14670 FOR I=1 TO NOBS:GET 3,K+I:NGR(I)=CVI(A9):TDBPWR(I)=CVS(B9):PULL(I)=CVS(C9)
14680 SLIP(I)=CVS(D9):VA(I)=CVS(E9):IRPM(I)=CVI(F9):NEXT:RETURN
14690 '*
14700 '* SUBROUTINE #15/C
14710 '*
14720 FOR I=1 TO NOBS:GET #3,K+I:PTOPWR(I)=CVS(A10):TAXPWR(I)=CVS(B10):TORQUE(I)=CVS(C10)
14730 TCWTR(I)=CVS(D10):TRRT(I)=CVS(E10):TDTR(I)=CVS(F10):TGTR(I)=CVS(G10):THRUST(I)=CVS(H10):NEXT:RETURN
14740 '*
14750 '* SUBROUTINE #15/D
14760 '*
14770 FOR I=1 TO NOBS:GET #3,K+I:TFCEFF(I)=CVS(A11):PWREFF(I)=CVS(B11):TREFF(I)=CVS(C11)
14780 TDFWT(I)=CVS(D11):TDRWT(I)=CVS(E11):RRTOTL(I)=CVS(F11):V(I)=CVS(G11):TEA(I)=CVS(H11):NEXT:RETURN
14790 '*
```

```
14800 '* SUBROUTINE #16 - SUPERVISOR
14810 '*
14820 N=1
14830 GOSUB 14950
14840 GOSUB 20260:PRINT "PgUp: Page Up   PgDn: Page Down   End: Terminate";TAB(70);"Page";N;:GOSUB 20330
14850 GOSUB 20810:ON LEN(A) GOTO 14850,14860
14860 A=RIGHT$(A,1):IF A=CHR$(73) THEN 14880
14870 IF A=CHR$(81) THEN 14900 ELSE IF A=CHR$(79) THEN 15200 ELSE BEEP:GOTO 14850
14880 IF N>1 THEN N=N-1 ELSE N=4
14890 GOTO 14910
14900 IF N<4 THEN N=N+1 ELSE N=1
14910 ON N GOSUB 14950,15050,15110,15160:GOTO 14840
14920 '*
14930 '* SUBROUTINE #16/A
14940 '*
14950 GOSUB 12080
14960 RESTORE 12720:GOSUB 20690:FOR I=1 TO 21:READ J1,J2,J3
14970 LOCATE J1,J2:PRINT E(I):NEXT:LOCATE 13,1:COLOR FNMC(1,9),FNMC(6,0)
14980 PRINT TAB(5);"SRWT";TAB(13);"ROL RES CF";TAB(28);"FRR";TAB(39);
14990 PRINT "RRR";TAB(48);"CGDIST";TAB(58);"PLDF(%)";TAB(69);"PLDR(%)
15000 PRINT:COLOR FNMC(15,7):PRINT USING FMT2;SRWT;
15010 PRINT USING FMT1;RRC;TRF;TRR;TCGDST;PLDF;PLDR:RETURN
15020 '*
15030 '* SUBROUTINE #16/B
15040 '*
15050 RESTORE 15820:GOSUB 15180:FOR I=1 TO NOBS:PRINT USING "##";NGR(I);
15060 PRINT USING FMT3;IRPM(I);:PRINT USING FMT1;TEA(I);
15070 PRINT USING FMT2;THRUST(I);TDBPWR(I);PTOPWR(I);TAXPWR(I);PULL(I):NEXT:RETURN
15080 '*
15090 '* SUBROUTINE #16/C
15100 '*
15110 RESTORE 15830:GOSUB 15180:FOR I=1 TO NOBS:PRINT USING "##";NGR(I);
15120 PRINT USING FMT1;VA(I);V(I);SLIP(I);TRRT(I);:PRINT USING FMT2;TDFWT(I);TDRWT(I);TCWTR(I):NEXT:RETURN
15130 '*
15140 '* SUBROUTINE #16/D
15150 '*
15160 RESTORE 15840:GOSUB 15180:FOR I=1 TO NOBS:PRINT USING "##";NGR(I);
15170 PRINT USING FMT1;TORQUE(I);TDTR(I);TGTR(I);TFCEFF(I);PWREFF(I);TREFF(I);RRTOTL(I):NEXT:RETURN
15180 MKBACK=6:GOSUB 20350:CODE="TRACTOR PERFORMANCE PARAMETERS":GOSUB 20370
15190 PRINT:COLOR FNMC(1,9):READ A:PRINT A:COLOR FNMC(15,7):RETURN
15200 CLOSE #3:COLOR ,2,2:RETURN
15210 '*
15220 '* PRINTOUT AN EXISTING FILE *
15230 '*
15240 MKBACK=2:GOSUB 20350:CODE="RETRIEVE A DATA BASE FILE":GOSUB 20370
15250 GOSUB 12230:GOSUB 12770:GOSUB 14330:GOSUB 15290:MODEL=0:GOTO 15240
15260 '*
15270 '* OUTPUT
```

```
15280 '*
15290 GOSUB 20260:GOSUB 20250:PRINT "Output to Screen or Printer (S/P) ?";
15300 GOSUB 20810:IF A="S" THEN 15340 ELSE IF A="P" THEN 15380 ELSE 15300
15310 '*
15320 '* SEND TO THE SCREEN
15330 '*
15340 GOSUB 14800:RETURN
15350 '*
15360 '* SEND TO THE PRINTER
15370 '*
15380 GOSUB 20250:PRINT "Wait! Printing is in progress.";:LPRINT
15390 IF NOBS<=8 THEN LPPF=0 ELSE IF NOBS<=11 THEN LPPF=2 ELSE LPPF=1
15400 COLOR 7:GOSUB 15480:GOSUB 15650:CLOSE #3:RETURN
15410 '* PRINTOUT HEADINGS
15420 DATA "TRACTOR","TEST LOCATION","TEST NUMBER","TEST DATE","RELEASE DATE","METHOD","SURFACE","TYPE OF HITCH"
15430 DATA "TIRES:  FRONT","REAR"
15440 DATA "TIRES:  INNER","OUTER"
15450 '*
15460 '* SUBROUTINE #17/A
15470 '*
15480 LPRINT:IF UNIT%=1 THEN APL="KW" ELSE APL="HP"
15490 E(1)=DESIGN:E(2)=ALOC:E(3)=CTNO:E(4)=DATE:E(5)=DATE$
15500 IF MODEL=0 THEN E(6)="NEBRASKA":E(7)=FSURF:E(8)="TOWED":GOTO 15560
15510 FOR I=6 TO 8:ON I-5 GOTO 15520,15530,15540
15520 RESTORE 17550:LGP=MODEL:GOTO 15550
15530 RESTORE 17560:LGP=LAND :GOTO 15550
15540 RESTORE 17570:LGP=IMPL
15550 FOR J=1 TO LGP:READ E(I):NEXT J,I
15560 RESTORE 15420:FOR I=1 TO 8:READ A:LPRINT TAB(20);CHR$(27);"E";A;CHR$(27);"F";TAB(40);E(I):NEXT
15570 IF TRAC%=4 THEN RESTORE 15440 ELSE RESTORE 15430
15580 READ A:LPRINT TAB(20);CHR$(27);"E";A;CHR$(27);"F";TAB(40);DFRONT;" :";IFPLY;":";PF;":";NUMF
15590 READ A:LPRINT TAB(28);CHR$(27);"E";A;CHR$(27);"F";TAB(40);DREAR;" :";IRPLY;":";PR;":";NUMR
15600 LPRINT TAB(20);CHR$(27);"E";APL;" @";OPRPM;"RPM";CHR$(27);"F";TAB(39);RATPWR
15610 LPRINT:LPRINT:LPRINT:RETURN
15620 '*
15630 '* SUBROUTINE #17/B
15640 '*
15650 RESTORE 15800:FOR I=1 TO 2:READ A:LPRINT TAB(10);CHR$(27);"E";A;CHR$(27);"F":ON I GOTO 15660,15670
15660 LPRINT TAB(6);:LPRINT USING FMT3;SFWT;SRWT;STOWT;OPRPM;:LPRINT USING FMT1;TRF;TRR:GOTO 15680
15670 LPRINT TAB(6);:LPRINT USING FMT1;TDBH;WHLBS;TCGDST;PLDF;PLDR;RRC
15680 LPRINT:LPRINT:LPRINT:NEXT
15690 RESTORE 15820:FOR J=1 TO 3:READ A:LPRINT CHR$(27);"E";A;CHR$(27);"F"
15700 FOR I=1 TO NOBS:ON J GOTO 15710,15730,15750
15710 LPRINT USING "##";NGR(I);:LPRINT USING FMT3;IRPM(I);:LPRINT USING FMT1;TEA(I);
15720 LPRINT USING FMT2;THRUST(I);TDBPWR(I);PTOPWR(I);TAXPWR(I);PULL(I):GOTO 15760
15730 LPRINT USING "##";NGR(I);:LPRINT USING FMT1;VA(I);V(I);SLIP(I);TRRT(I);
15740 LPRINT USING FMT2;TDFWT(I);TDRWT(I);TCWTR(I):GOTO 15760
15750 LPRINT USING "##";NGR(I);:LPRINT USING FMT1;TORQUE(I);TDTR(I);TGTR(I);TFCEFF(I);PWREFF(I);TREFF(I);RRTOTL(I)
```

```
15760 NEXT:IF LPPF=J THEN LPRINT CHR$(12);
15770 LPRINT:LPRINT:LPRINT:NEXT:LPRINT CHR$(12);:GOSUB 20250
15780 RETURN
15790 '* PRINTOUT PARAMETER HEADINGS
15800 DATA "SFWT        SRWT        STOWT     RATED RPM       FRR         RRR"
15810 DATA " DBH        WHLBS       CGDIST     PLDF (%)   PLDR (%)    MT RES CF"
15820 DATA "GR    ENG RPM    TR EF ARM      THRUST     DB POWER   PTO POWER  AXLE POWER     PULL   "
15830 DATA "GR   GND SPEED   TH SPEED       SLIP        TRV RAT      DFWT         DRWT       CALWTR   "
15840 DATA "GR    TORQUE        DTR          GTR        FRC EFF    PWR COEFF    TREFFY      RRTOTL   "
15850 '*
15860 '* SIMULATION *
15870 '*
15880 IF DBASE%=2 THEN GOSUB 20610:GOTO 10700 ELSE MKBACK=2:GOSUB 20350:CODE="SIMULATION MODEL"
15890 GOSUB 20370:GOSUB 12230:GOSUB 12770:GOSUB 14330:IF IDERR=1 THEN GOSUB 20420:GOTO 15880
15900 CLOSE #3:IF IDERR>0 THEN GOSUB 20410:GOTO 15890 ELSE GOSUB 20300:GOSUB 15990:IF MODEL=1 THEN 15940
15910 PTR%=6:GOSUB 20250:PRINT "Specify Cone Index [     ]";:J1=24:J2=21:J3=4:GOSUB 17760
15920 PTR%=0:VCNIX=VAL(ALPHA):IF VCNIX=0 THEN VCNIX=(4-LAND)*350
15930 GOSUB 20260:PRINT "Cone Index set to";VCNIX;"kPa";
15940 GOSUB 20250:PRINT "Open Simulation output file (Y/N)?";
15950 GOSUB 20810:ANSR=A:IF ANSR="Y" OR ANSR="N" THEN GOSUB 11350 ELSE 15950
15960 COLOR 15:LOCATE 12,1:PRINT "Simulation is in progress.....";
15970 GOSUB 11680:GOSUB 17160:GOSUB 17290:ON MODEL GOTO 16210,16700,16950
15980 '*
15990 '* SELECT MODEL, LAND & IMPLEMENT
16000 '*
16010 FOR J=0 TO 2:COLOR 15:INGA(11)=5:INGA(12)=13:INGA(13)=J*26+3:INGA(14)=J*26+20:GOSUB 20630:J3=J*26+5
16020 LOCATE 7,J3:COLOR 1:ON J+1 GOTO 16030,16040,16050
16030 PRINT "SIMULATION MODEL":RESTORE 17550:GOTO 16060
16040 PRINT "  TYPE OF SOIL  ":RESTORE 17560:GOTO 16060
16050 PRINT " TYPE OF HITCH  ":RESTORE 17570
16060 J1=9:J2=13:J3=J3+1:GOSUB 20400:NEXT
16070 PTR%=7:INGA(1)=4:INGA(2)=9:INGA(3)=13:INGA(4)=2:INGA(5)=6:INGA(6)=15:INGA(7)=14:
16080 INGA(8)=2:INGA(15)=0:GOSUB 17890:MODEL=INDEX:PTR%=8:INGA(1)=5:INGA(5)=32:GOSUB 17890:
16090 LAND=INDEX:PTR%=9:INGA(1)=6:INGA(5)=58:GOSUB 17890:IMPL=INDEX
16100 CLASS="S"+RIGHT$(STR$(LAND),1)+"I"+RIGHT$(STR$(IMPL),1):EXT2=".ML"+RIGHT$(STR$(MODEL),1)
16110 IF MENU=6 THEN FILEO=CTNO+CLASS+EXT2 ELSE ASYST=CLASS:EXT1=EXT2
16120 RETURN
16130 '* QUADRANT 1 - DATA
16140 DATA -.0201,.1111,400,-.01697,.1381,500,-.01659,.16455,600,.001497,.18968
16150 DATA 700,-.02521,.2192,800,-.02617,.24677,900,-.016,.27375,1000,-.04,.30297
16160 DATA 1100,-.05849,.3301,1200,-.031696,.3515,1300,-.04917,.38027,1400,-.0618
16170 DATA .4356,1600,-.031,.51647,2000,-.1441,.63464,2400
16180 '*
16190 '* MODEL 1
16200 '*
16210 FOR I=1 TO NOBS:GOSUB 17240
16220 '* QUADRANT #1
16230 PRMTR=SRWT*UCF*1000/TAXPWR(I):RESTORE 16140
```

```
16240 FOR J=1 TO 14:READ TA,TB,INGA(J):RGP(60+J)=TA+V(I)*TB:NEXT:L=1
16250 WHILE L<14:IF PRMTR=>INGA(L) AND PRMTR<INGA(L+1) THEN 16270 ELSE L=L+1
16260 WEND:ERROR 200
16270 X=RGP(60+L)+(PRMTR-INGA(L))/(INGA(L+1)-INGA(L))*(RGP(61+L)-RGP(60+L))
16280 '* QUADRANT #2
16290 ON LAND GOTO 16350,16370,16390
16300 '* QUADRANT 2 - DATA
16310 DATA -.02729,.07707,25.17217,-1.5084,-.06178,.08248
16320 DATA 27.767,-1.6026,-.06178,.08248,44.84557,-1.92993
16330 DATA 117.3558,-86.7916,23.3799,-2.1465,120.4186,-84.2187
16340 DATA 21.3694,-1.8515,134.5241,-93.02687,23.1864,-1.97
16350 RESTORE 16310:FOR J=1 TO IMPL:GOSUB 16610:NEXT:ON IMPL GOSUB 16650,16640,16650
16360 GOTO 16400
16370 RESTORE 16320:FOR J=1 TO IMPL:GOSUB 16610:NEXT:ON IMPL GOSUB 16640,16650,16640
16380 GOTO 16400
16390 RESTORE 16330:FOR J=1 TO IMPL:GOSUB 16600:NEXT:GOSUB 16620
16400 SLIP(I)=Y:IF SLIP(I)>30.5 AND SRWT<=(NUMR*LDR) THEN SRWT=SRWT+10:GOTO 16230
16410 X=Y:STOWT=SRWT+SFWT:TRRT(I)=FNTRRT:VA(I)=V(I)*TRRT(I)
16420 '* QUADRANT #3
16430 '* PULL RATIO
16440 ON LAND GOTO 16450,16460,16470
16450 RESTORE 16560:GOTO 16480 '* FIRM
16460 RESTORE 16570:GOTO 16480 '* TILLED
16470 RESTORE 16580            '* SOFT
16480 FOR J=1 TO IMPL:GOSUB 16600:NEXT:GOSUB 16620:PRMTR=Y:PULL(I)=PRMTR*(SRWT*L2+STOWT*(1-L2))*UCF
16490 GOSUB 17210:THRUST(I)=PULL(I)+RRTOTL(I):TDTR(I)=FNTDTR:TGTR(I)=FNTGTR
16500 TFCEFF=FNTFCEFF:PWREFF(I)=FNPWREFF:GOSUB 17140
16510 '* TRACTIVE EFFICIENCY
16520 RESTORE 16590:FOR J=1 TO LAND:GOSUB 16600:NEXT:GOSUB 16620
16530 TREFF(I)=Y:TDBPWR(I)=TREFF(I)*TAXPWR(I)*L1
16540 NEXT:GOTO 17480
16550 '* QUADRANT 3 - DATA
16560 DATA -.03845,.06798,-.00129,9.2E-06,-.0285,.0673,-.00194,.000024,-.0269,.05979,-.0017,.000019
16570 DATA -.02613,.0517,-.001297,.000015,-.02124,.0482,-.001275,.000014,-.02263,.0459,-.00136,.000017
16580 DATA -.0732,.03827,-.00124,.000015,-.06959,.03496,-.0011,.000013,-.0715,.03277,-.001,.0000114
16590 DATA .3993,.0828,-.0052,.00009,.28685,.06498,-.00356,.000055,.20415,.05,-.0023,.000029
16600 READ TA,TB,TC,TD:RETURN
16610 READ TA,TB:RETURN
16620 K=80:GOSUB 19530:Y=RGP(80):RETURN
16630 K=80:GOSUB 19480:Y=RGP(80):RETURN
16640 K=80:GOSUB 19500:Y=RGP(80):RETURN
16650 K=80:GOSUB 19470:Y=RGP(80):RETURN
16660 K=80:GOSUB 19450:Y=RGP(80):RETURN
16670 '*
16680 '* MODEL 2
16690 '*
16700 K1=LEN(DFRONT)-FNLSTR(DFRONT,"X"):RGP(79)=RATPWR/OPRPM
16710 K2=LEN(DREAR)-FNLSTR(DREAR,"X"):PRMTR=.9746*UNIT%-.9492
```

```
16720 RGP(61)=VAL(RIGHT$(DFRONT,K1))*PRMTR:RGP(62)=VAL(RIGHT$(DREAR,K2))*PRMTR
16730 FOR I=1 TO NOBS:XINC=.1
16740 SLIP=.001:TCWTR(I)=0
16750 TDRWT(I)=FNTDRWT:TDFWT(I)=FNTDFWT:RGP(63)=FNTHEL2:RGP(64)=FNTHEL1
16760 RGP(65)=(TDF-RGP(61))/2:RGP(66)=(TDR-RGP(62))/2
16770 RGP(I)=VCNIX*TWF*TDF*SQR(RGP(63)/RGP(65))/(TDFWT(I)*(1+(TWF*.5/TDF))*UCF)
16780 RGP(20+I)=VCNIX*TWR*TDR*SQR(RGP(64)/RGP(66))/(TDRWT(I)*(1+(TWR*.5/TDR))*UCF)
16790 RRCF=.049+(.287/RGP(I)):RGP(71)=RRCF*TDFWT(I)*UCF 'NUMF*
16800 RRCR=.049+(.287/RGP(20+I)):RGP(72)=RRCR*TDRWT(I)*UCF:RRTOTL(I)=RGP(71)+RGP(72) 'NUMR*
16810 RGP(73)=.796-(.92/RGP(20+I)):RGP(74)=(4.838+.061*RGP(20+I))/RGP(73)
16820 RGP(75)=RGP(73)*(1-EXP(-(RGP(74)*SLIP))):IF TRAC%<3 THEN 16850
16830 RGP(73)=.796-(.92/RGP(I)):RGP(74)=(4.838+.061*RGP(I))/RGP(73)
16840 RGP(77)=RGP(73)*(1-EXP(-(RGP(74)*SLIP)))
16850 RGP(76)=(NUMR*RGP(75)*TDRWT(I)+NUMF*RGP(77)*TDFWT*(1-L2))*UCF
16860 PULL(I)=RGP(76)-RGP(71)*L2:THRUST(I)=RGP(76)+RGP(72)+RGP(71)*(1-L2)
16870 PRMTR=FNTCWTR2:IF PRMTR>TCWTR(I) THEN TCWTR(I)=PRMTR:GOTO 16750 '+PULL(I)*.1*(3-IMPL)/UCF
16880 PRMTR=THRUST(I)*TEA(I):IF PRMTR<TORQUE(I)*L1 THEN 16900
16890 IF XINC<=.0001 THEN 16910 ELSE SLIP=SLIP-XINC:XINC=XINC/10
16900 SLIP=SLIP+XINC:IF SLIP>.2 AND SRWT<NUMR*LDR THEN SRWT=SRWT+10:STOWT=SFWT+SRWT:GOTO 16740 ELSE 16750
16910 SLIP(I)=SLIP*100:GOSUB 17180:NEXT:GOTO 17480
16920 '*
16930 '* MODEL 3
16940 '*
16950 FOR I=1 TO NOBS:GOSUB 17240
16960 SLIP=0:XINC=.1:TDFWT(I)=SFWT
16970 PRMTR=(SRWT+SFWT*(1-L2))*UCF
16980 PULL(I)=EXP(-.3*VCNIX*TWR*TDR*(NUMR+NUMF*(1-L2))*SLIP/PRMTR)
16990 PULL(I)=.75*(1-PULL(I))*PRMTR-RRTOTL(I)
17000 TCWTR(I)=FNTCWTR2:TDRWT(I)=FNTDRWT+PULL(I)*.15*(3-IMPL)/UCF:TDFWT(I)=FNTDFWT
17010 IF (TDRWT(I)+TDFWT(I)*(1-L2))*UCF<=PRMTR THEN 17030
17020 PRMTR=(TDRWT(I)+TDFWT(I)*(1-L2))*UCF:GOTO 16980
17030 PRMTR=(PULL(I)+RRTOTL(I))*TEA(I):IF PRMTR<TORQUE(I)*L1 THEN 17050
17040 IF XINC<=.0001 THEN 17090 ELSE SLIP=SLIP-XINC:XINC=XINC/10
17050 SLIP=SLIP+XINC:IF SLIP>.05*(7-VCNIX/350) THEN 17060 ELSE 16970
17060 IF TRAC%<3 THEN IF SRWT=>NUMR*LDR THEN 16970 ELSE 17080
17070 IF SFWT<NUMF*LDF THEN SFWT=SFWT+10
17080 IF SRWT<NUMR*LDR THEN SRWT=SRWT+10:STOWT=SFWT+SRWT:GOTO 16960
17090 STOWT=SFWT+SRWT:SLIP(I)=SLIP*100:THRUST(I)=PULL(I)+RRTOTL(I)
17100 GOSUB 17140:GOSUB 17180:NEXT:GOTO 17480
17110 '*
17120 '* GENERAL PURPOSE EQUATIONS
17130 '*
17140 TEA(I)=(TDR/2)-FNTHEL1:IF TRAC%>2 THEN TEA(I)=(TEA(I)+(TDF/2)-FNTHEL2)/2
17150 RETURN
17160 IF TRAC%<3 THEN L1=1:L2=1 ELSE L1=2:L2=0  'L1=NO. OF AXLES - L2=TYPE OF WEIGHT
17170 RETURN
17180 GOSUB 17210:GOSUB 17190:GOSUB 17200:GOSUB 17220:GOSUB 17230:RETURN
17190 TRRT(I)=FNTRRT:VA(I)=V(I)*TRRT(I):RETURN
```

```
17200 TDBPWR(I)=PULL(I)*VA(I)/3.6:RETURN
17210 TCWTR(I)=FNTCWTR2:TDRWT(I)=FNTDRWT:TDFWT(I)=FNTDFWT:RETURN
17220 TDTR(I)=FNTDTR:TGTR(I)=FNTGTR:TFCEFF(I)=FNTFCEFF:RETURN
17230 TREFF(I)=FNTREFF:PWREFF(I)=FNPWREFF:RETURN
17240 RRTOTL(I)=FNRRTOTL:RETURN
17250 GOSUB 17140:THRUST(I)=TORQUE(I)*2*L1/TEA(I):RETURN
17260 '*
17270 '* ROLL RES COEFF FOR SOIL
17280 '*
17290 RGP(71)=TDF*1000:RGP(72)=TDR*1000:IF MODEL>0 THEN RESTORE 17420 ELSE RESTORE 17440:LAND=1
17300 GOSUB 16600:FOR I=1 TO 2:X=RGP(70+I):GOSUB 16620:RGP(70+I)=Y*LAND:NEXT
17310 RESTORE 17430:FOR I=1 TO 4:READ INGA(I):GOSUB 16610
17320 X=RGP(71):GOSUB 16660:RGP(60+I)=Y:X=RGP(72):GOSUB 16660:RGP(64+I)=Y:NEXT
17330 PRMTR=PF:L=1:GOSUB 17350:RRCF=RRC:PRMTR=PR:L=1:GOSUB 17350:RRCR=RRC*(1-TRAC%*.05)
17340 RRC=RRCF+RRCR:RETURN
17350 IF PRMTR<70 THEN RGP(60)=0:INGA(5)=0:GOTO 17400
17360 IF PRMTR<100 THEN RGP(60)=RGP(61):INGA(5)=INGA(1):GOTO 17400
17370 IF PRMTR>200 THEN L=2
17380 IF PRMTR>150 THEN RGP(60)=RGP(64):INGA(5)=INGA(4):GOTO 17400
17390 IF PRMTR>100 THEN RGP(60)=RGP(63):INGA(5)=INGA(3)
17400 RRC=RGP(62)+(PRMTR-100*L)*(RGP(60)-RGP(62))/(INGA(5)-100):RETURN
17410 '* ROLLING RESISTANCE - DATA
17420 DATA .0958,-.000091,4.5E-08,0!,.23327,-.00013,-2.4E-09,0!,.59835,-.000763,5.2E-07,-1.0E-10
17430 DATA 70,.00577,.87526,100,.000288,1.02078,150,-.0087,1.21117,200,-.01523,1.43489
17440 DATA .0851,-.000106,5.24E-08,0!
17450 '*
17460 '* END OF SIMULATION MODELS
17470 '*
17480 LOCATE 12,31:COLOR FNMC(15,0),FNMC(1,7):PRINT "Simulation terminated.":COLOR FNMC(10,7),1
17490 GOSUB 20240:IF ANSR="N" THEN GOSUB 15290:GOTO 15880
17500 FILE1="SIM_"+ASYST+EXT1:SWAP FILE1,DBASE:SWAP FILEOUT,FILEO:SWAP DUMMY,DD
17510 IF DUMMY="A:" THEN DD="B:" ELSE DD="A:"
17520 GOSUB 17630:GOSUB 20520:PRINT "transfer data to ";FILEOUT;"...";:GOSUB 13770
17530 CLOSE #3:PRINT "OK";:SWAP FILE1,DBASE:SWAP FILEOUT,FILEO:SWAP DUMMY.DD:GOTO 15880
17540 '* SIMULATION OPTIONS - LABELS
17550 DATA " ASAE  D230.4 ","     OECD     ","    HELLAS    "
17560 DATA "     FIRM     ","    TILLED    ","     SOFT     "
17570 DATA "   INTEGRAL   "," SEMI-MOUNTED ","    TOWED     "
17580 '*
17590 '****************** SERVICE ROUTINES - GROUP 1 ***************************
17600 '*
17610 '* UPDATE DIRECTORY
17620 '*
17630 N=2:GOSUB 11920:GOSUB 20540:GET #2,1:LIMIT=CVI(FMARK):CODE=DESIGN:CLASS=FILEOUT
17640 WHILE N<=LIMIT+1:GET #2,N:A=FDIR1:B=FDIR2
17650 IF CLASS>B THEN GOSUB 20260:PRINT "Record";N-1;"skipped.";:N=N+1:GOTO 17670
17660 IF CLASS=B THEN GOSUB 20240:PRINT FILEOUT;" exists...";:GOTO 17720 ELSE 17680
17670 WEND:GOTO 17700
```

```
17680 WHILE N<=LIMIT+1:LSET FDIR1=CODE:LSET FDIR2=CLASS:PUT #2,N
17690 SWAP A,CODE:SWAP B,CLASS:N=N+1:GET #2,N:A=FDIR1:B=FDIR2:WEND
17700 LSET FDIR1=CODE:LSET FDIR2=CLASS:PUT #2,N:RSET FMARK=MKI$(LIMIT+1):PUT #2,1:CLOSE #2
17710 GOSUB 20240:PRINT FILEOUT;" was added...";
17720 RETURN
17730 '*
17740 '* GENERAL PURPOSE EDITOR
17750 '*
17760 EDI%=0:ALPHA=""
17770 GOSUB 20810:COLOR 15:ON LEN(A) GOTO 17780,17810
17780 IF A=CHR$(27) THEN ALPHA=CHR$(27):GOTO 17850 ELSE IF A=CHR$(13) THEN 17840
17790 IF A=CHR$(8) THEN 17820 ELSE IF EDI%=J3 THEN 17810
17800 IF ASC(A)>31 AND ASC(A)<125 THEN 17830
17810 BEEP:GOTO 17770
17820 IF EDI%=0 THEN 17810 ELSE LOCATE J1,FNQ(EDI%):A=" ":PRINT A;:EDI%=EDI%-1:ALPHA=LEFT$(ALPHA,EDI%):GOTO 17770
17830 EDI%=EDI%+1:ALPHA=ALPHA+A:LOCATE J1,FNQ(EDI%):PRINT A;:GOTO 17770
17840 IF ALPHA="" THEN ALPHA=CHR$(13)
17850 EDI%=0:RETURN
17860 '*
17870 '* OPTION SELECTION SUBROUTINE
17880 '*
17890 GOSUB 18030:INDEX=INGA(2):COLOR FNMC(INGA(7),0),FNMC(INGA(8),7)
17900 GOSUB 18060:READ ALPHA:GOSUB 17990:LOCATE INGA(2),LMG:PRINT ALPHA;
17910 GOSUB 20810:ON LEN(A) GOTO 17940,17920
17920 A=RIGHT$(A,1):IF A=CHR$(79) THEN INDEX=(INDEX-INGA(2))/INGA(4)+1:RETURN
17930 IF A=CHR$(77) OR A=CHR$(80) THEN 17950 ELSE IF A=CHR$(72) OR A=CHR$(75) THEN 17970
17940 IF A=CHR$(27) THEN 20110 ELSE BEEP:GOTO 17910
17950 GOSUB 18000:GOSUB 18010:IF INDEX=INGA(3) THEN INDEX=INGA(2) ELSE INDEX=INDEX+INGA(4)
17960 GOTO 17980
17970 GOSUB 18000:GOSUB 18010:IF INDEX=INGA(2) THEN INDEX=INGA(3) ELSE INDEX=INDEX-INGA(4)
17980 GOSUB 18000:GOSUB 18020:GOTO 17910
17990 ICOUNT=INGA(2)*INGA(15)+INDEX*(1-INGA(15)):LMG=INGA(5)+INGA(15)*(INDEX-INGA(2))*13:RETURN
18000 GOSUB 18060:FOR I=INGA(2) TO INDEX STEP INGA(4):READ ALPHA:NEXT:GOSUB 17990:LOCATE ICOUNT,LMG:RETURN
18010 COLOR FNMC(INGA(6),15),FNMC(INGA(8),0):PRINT ALPHA;:RETURN
18020 COLOR FNMC(INGA(7),0),FNMC(INGA(8),7):PRINT ALPHA;:RETURN
18030 GOSUB 20240:PRINT CHR$(26);" or ";CHR$(25);": Next Option   ";CHR$(27);
18040 PRINT " or ";CHR$(24);": Previous Option   End: Select Option";
18050 COLOR INGA(6):RETURN
18060 ON INGA(1) GOTO 18070,18080,18090,18100,18110,18120,18130,18140,18150,18160
18070 RESTORE 10830:RETURN
18080 RESTORE 12040:RETURN
18090 RETURN
18100 RESTORE 17550:RETURN
18110 RESTORE 17560:RETURN
18120 RESTORE 17570:RETURN
18130 RESTORE 21590:RETURN
18140 RESTORE 21620:RETURN
18150 RESTORE 22870:RETURN
```

```
18160 RESTORE 23350:RETURN
18170 '*
18180 '***************************** END - GROUP 1 *****************************
18190 '*
18200 '* COMMUNICATIONS PACKAGE *
18210 '*
18220 MKBACK=2:GOSUB 20350:CODE="IBM SERIAL COMMUNICATIONS":GOSUB 20370
18230 GOSUB 20250:PRINT "No Communications available";:GOSUB 20890:GOTO 10700 '* :CALL IBMCOMM
18240 '*
18250 '* STATISTICAL ANALYSIS
18260 '*
18270 LMG=IGROUP:INDEX=40:GOSUB 18420:LMG=JGROUP:INDEX=60:GOSUB 18420:RESTORE 18380
18280 ICOUNT=1:WHILE ICOUNT<5:READ LMG:IF IGROUP=LMG OR JGROUP=LMG THEN TRANS%=1:GOTO 18300
18290 ICOUNT=ICOUNT+1:WEND:TRANS%=0
18300 L=1:FOR I=1 TO NOBS:RGP(I)=RGP(40+I):RGP(20+I)=RGP(60+I):NEXT:GOSUB 18700
18310 L=2:FOR I=1 TO NOBS:RGP(20+I)=LOG(RGP(60+I)):NEXT:GOSUB 18700
18320 RX(L)=EXP(RX(L)):L=3:FOR I=1 TO NOBS:RGP(20+I)=1/RGP(60+I):NEXT:GOSUB 18700
18330 L=4:FOR I=1 TO NOBS:RGP(I)=1/RGP(40+I):RGP(20+I)=RGP(60+I):NEXT:GOSUB 18700
18340 L=5:FOR I=1 TO NOBS:RGP(I)=LOG(RGP(40+I)):NEXT:GOSUB 18700
18350 L=6:FOR I=1 TO NOBS:RGP(20+I)=LOG(RGP(60+I)):NEXT:GOSUB 18700
18360 RX(L)=EXP(RX(L)):L=7:FOR I=1 TO NOBS:RGP(20+I)=1/RGP(60+I):RGP(I)=1/RGP(40+I):NEXT:GOSUB 18700
18370 SWAP SLP(7),RX(7):GOTO 18850
18380 DATA 3,20,21,22
18390 '*
18400 '* CURVE FITTING
18410 '*
18420 FOR I=1 TO NOBS
18430 ON LMG GOTO 18440,18450,18460,18470,18480,18490,18500,18510,18520,18530,18540,_
18440 RGP(INDEX+I)=TFCEFF(I):GOTO 18660
18450 RGP(INDEX+I)=TREFF(I):GOTO 18660
18460 RGP(INDEX+I)=IRPM(I):GOTO 18660
18470 RGP(INDEX+I)=NGR(I):GOTO 18660
18480 RGP(INDEX+I)=RRTOTL(I):GOTO 18660
18490 RGP(INDEX+I)=PULL(I):GOTO 18660
18500 RGP(INDEX+I)=TAXPWR(I):GOTO 18660
18510 RGP(INDEX+I)=PWREFF(I):GOTO 18660
18520 RGP(INDEX+I)=TDBPWR(I):GOTO 18660
18530 RGP(INDEX+I)=PTOPWR(I):GOTO 18660
18540 RGP(INDEX+I)=TDTR(I):GOTO 18660
18550 RGP(INDEX+I)=TGTR(I):GOTO 18660
18560 RGP(INDEX+I)=TRRT(I):GOTO 18660
18570 RGP(INDEX+I)=SLIP(I):GOTO 18660
18580 RGP(INDEX+I)=VA(I):GOTO 18660
18590 RGP(INDEX+I)=V(I):GOTO 18660
18600 RGP(INDEX+I)=THRUST(I):GOTO 18660
18610 RGP(INDEX+I)=TEA(I):GOTO 18660
18620 RGP(INDEX+I)=TORQUE(I):GOTO 18660
18630 RGP(INDEX+I)=TDFWT(I):GOTO 18660
```

```
18640 RGP(INDEX+I)=TDRWT(I):GOTO 18660
18650 RGP(INDEX+I)=TCWTR(I)
18660 NEXT:RETURN
18670 '*
18680 '* SIMPLE REGRESSION SUBROUTINE
18690 '*
18700 IF TRANS%=1 AND L<>5 AND L<>6 THEN GOSUB 18810
18710 TMAT#(1,2)=0:RMAT#(1)=0:TMAT#(1,3)=0:SMAT#(1)=0:RMAT#(2)=0
18720 FOR I=1 TO NOBS:TMAT#(1,2)=TMAT#(1,2)+RGP(I):RMAT#(1)=RMAT#(1)+RGP(20+I)
18730 TMAT#(1,3)=TMAT#(1,3)+RGP(I) 2:SMAT#(1)=SMAT#(1)+RGP(20+I) 2:RMAT#(2)=RMAT#(2)+RGP(I)*RGP(20+I):NEXT
18740 SLP(L)=(NOBS*RMAT#(2)-TMAT#(1,2)*RMAT#(1))/(NOBS*TMAT#(1,3)-TMAT#(1,2) 2):RX(L)=(RMAT#(1)-SLP(L)*TMAT#(1,2))/NOBS
18750 RCC=(RMAT#(2)-TMAT#(1,2)*RMAT#(1)/NOBS)/(SQR((TMAT#(1,3)-TMAT#(1,2) 2/NOBS)*(SMAT#(1)-RMAT#(1) 2/NOBS)))
18760 SSE#=SMAT#(1)-(RMAT#(1) 2/NOBS)-SLP(L)*(RMAT#(2)-TMAT#(1,2)*RMAT#(1)/NOBS)
18770 IF SSE#<0 THEN R2(L)=0 ELSE R2(L)=RCC 2
18780 IF TRANS%=1 THEN RESTORE 19110 ELSE 18800
18790 FOR I=1 TO L:READ TA,TB:NEXT:SLP(L)=SLP(L)*TA:RX(L)=RX(L)*TB
18800 RETURN
18810 FOR I=1 TO NOBS:RGP(I)=RGP(40+I)*.01:RGP(20+I)=RGP(60+I)*.01:NEXT:RETURN
18820 '*
18830 '* MULTIPLE REGRESSION SUBROUTINE
18840 '*
18850 IF TRANS%=1 THEN GOSUB 18810:GOTO 18870
18860 FOR I=1 TO NOBS:RGP(I)=RGP(40+I):RGP(20+I)=RGP(60+I):NEXT
18870 FOR I=1 TO 4:FOR J=1 TO 4:TMAT#(I,J)=0:NEXT:RMAT#(I)=0:SMAT#(I)=0:NEXT
18880 SY2#=0:FOR I=1 TO NOBS:TMAT#(1,2)=TMAT#(1,2)+RGP(I)
18890 TMAT#(1,3)=TMAT#(1,3)+RGP(I) 2:TMAT#(1,4)=TMAT#(1,4)+RGP(I) 3
18900 TMAT#(2,4)=TMAT#(2,4)+RGP(I) 4:TMAT#(3,4)=TMAT#(3,4)+RGP(I) 5:TMAT#(4,4)=TMAT#(4,4)+RGP(I) 6
18910 RMAT#(1)=RMAT#(1)+RGP(20+I):SY2#=SY2#+RGP(20+I) 2:RMAT#(2)=RMAT#(2)+RGP(I)*RGP(20+I)
18920 RMAT#(3)=RMAT#(3)+(RGP(I) 2)*RGP(20+I):RMAT#(4)=RMAT#(4)+(RGP(I) 3)*RGP(20+I):NEXT
18930 TMAT#(1,1)=NOBS:TMAT#(2,1)=TMAT#(1,2):TMAT#(2,2)=TMAT#(1,3):TMAT#(3,1)=TMAT#(1,3)
18940 TMAT#(2,3)=TMAT#(1,4):TMAT#(3,2)=TMAT#(1,4):TMAT#(4,1)=TMAT#(1,4)
18950 TMAT#(3,3)=TMAT#(2,4):TMAT#(4,2)=TMAT#(2,4):TMAT#(4,3)=TMAT#(3,4)
18960 IROW=3:ICOL=3:JROW=3:GOSUB 19130
18970 PA1=SMAT#(1):PB1=SMAT#(2):PC1=SMAT#(3):SSR#=0
18980 FOR I=1 TO 3:SSR#=SSR#+SMAT#(I)*RMAT#(I):NEXT:IF SSR#>SY2# THEN R2(8)=0:GOTO 19000
18990 R2(8)=(SSR#-RMAT#(1) 2/NOBS)/(SY2#-RMAT#(1) 2/NOBS)
19000 IROW=4:ICOL=4:JROW=4:GOSUB 19130
19010 PA2=SMAT#(1):PB2=SMAT#(2):PC2=SMAT#(3):PD2=SMAT#(4):SSR#=0
19020 FOR I=1 TO 4:SSR#=SSR#+SMAT#(I)*RMAT#(I):NEXT:IF SSR#>SY2# THEN R2(9)=0:GOTO 19060
19030 R2(9)=(SSR#-RMAT#(1) 2/NOBS)/(SY2#-RMAT#(1) 2/NOBS)
19040 IF TRANS%=1 THEN PA1=PA1*100 ELSE 19060
19050 PB1=PB1*1:PC1=PC1*.01:PA2=PA2*100:PB2=PB2*1:PC2=PC2*.01:PD2=PD2*.0001
19060 PRMTR=0:IEQ=0:FOR I=1 TO 9:IF R2(I)>=PRMTR THEN PRMTR=R2(I):IEQ=I
19070 NEXT:IF IEQ<=7 THEN TA=RX(IEQ):TB=SLP(IEQ):TC=0:TD=0:GOTO 19090
19080 IF IEQ=8 THEN TA=PA1:TB=PB1:TC=PC1:TD=0 ELSE TA=PA2:TB=PB2:TC=PC2:TD=PD2
19090 RETURN
19100 '* DATA TRANSFORMATION PARAMETERS
19110 DATA 100!,1!,100!,.01,.01,.0001,100!,10000!,1!,1!,1!,1!,1!,.01
```

```
19120 '*
19130 '* MATRIX DIVISION SUBROUTINE
19140 '*
19150 ICOL=ICOL*2:DUMM#=1:PDET#=0:NDET#=0:TDET#=0
19160 FOR I=1 TO IROW:FOR J=0 TO ICOL-1:VMAT#(I,J+1)=TMAT#(I,(J MOD IROW)+1):NEXT J,I
19170 FOR I=0 TO IROW-1:FOR J=1 TO IROW:DUMM#=VMAT#(J,J+I)*DUMM#:NEXT J:PDET#=PDET#+DUMM#:DUMM#=1
19180 FOR J=IROW TO 1 STEP -1:DUMM#=VMAT#(J,IROW+1-J+I)*DUMM#:NEXT J:NDET#=NDET#+DUMM#:DUMM#=1:NEXT I:TDET#=PDET#-NDET#
19190 '*
19200 '* MATRIX INVERSION SUBROUTINE
19210 '*
19220 FOR K1=1 TO IROW:FOR K2=1 TO IROW:L=1:M=1
19230 FOR I=1 TO IROW:IF I=K1 THEN 19270
19240 FOR J=1 TO IROW:IF J=K2 THEN 19260
19250 VMAT#(L,M)=TMAT#(I,J):VMAT#(L,M+IROW-1)=TMAT#(I,J):M=M+1
19260 NEXT J:M=1:L=L+1
19270 NEXT I:IF IROW=4 THEN 19290
19280 QMAT#(K1,K2)=(VMAT#(1,1)*VMAT#(2,2))-(VMAT#(1,2)*VMAT#(2,1)):GOTO 19330
19290 PDET#=0:NDET#=0:FOR N1=0 TO IROW-2:DUMM#=1:FOR O=1 TO IROW-1
19300 DUMM#=VMAT#(O,O+N1)*DUMM#:NEXT O
19310 PDET#=PDET#+DUMM#:DUMM#=1:FOR O=IROW-1 TO 1 STEP -1:DUMM#=VMAT#(O,IROW-O+N1)*DUMM#:NEXT O
19320 NDET#=NDET#+DUMM#:DUMM#=1:NEXT N1:QMAT#(K1,K2)=PDET#-NDET#
19330 NEXT K2,K1
19340 FOR I=1 TO IROW-1:FOR J=I+1 TO IROW:SWAP QMAT#(I,J),QMAT#(J,I):NEXT J,I
19350 FOR I=1 TO IROW:L=(-1) I:FOR J=1 TO IROW:L=L*(-1):QMAT#(I,J)=QMAT#(I,J)*L/TDET#:NEXT J,I
19360 IF IROW=3 THEN 19390
19370 PRM#=0:FOR I=1 TO IROW:PRM#=PRM#+QMAT#(1,I)*TMAT#(I,1):NEXT:PRM#=1/PRM#
19380 FOR I=1 TO IROW:FOR J=1 TO IROW:VMAT#(I,J)=QMAT#(I,J):QMAT#(I,J)=QMAT#(I,J)*PRM#:NEXT J,I
19390 FOR I=1 TO IROW:SMAT#(I)=0:FOR K=1 TO IROW:SMAT#(I)=SMAT#(I)+QMAT#(I,K)*RMAT#(K)
19400 NEXT K,I:RETURN
19410 '*
19420 '* SUBROUTINE #18
19430 '*
19440 ON IEQ GOTO 19450,19460,19470,19480,19490,19500,19510,19520,19530
19450 RGP(K)=TA+TB*X:GOTO 19540
19460 RGP(K)=TA+EXP(TB*X):GOTO 19540
19470 RGP(K)=1/(TA+TB*X):GOTO 19540
19480 RGP(K)=TA+TB/X:GOTO 19540
19490 RGP(K)=TA+TB*LOG(X):GOTO 19540
19500 RGP(K)=TA*X TB:GOTO 19540
19510 RGP(K)=X/(TA+TB*X):GOTO 19540
19520 RGP(K)=TA+TB*X+TC*X 2:GOTO 19540
19530 RGP(K)=TA+TB*X+TC*X 2+TD*X 3
19540 RETURN
19550 '*
19560 '* GRAPHICS *
19570 '*
19580 GOSUB 19610:GOSUB 12230:GOSUB 12770:GOSUB 14330
19590 IF IDERR=1 THEN GOSUB 20420:GOTO 19580 ELSE IF NOBS>3 THEN GOSUB 20300:GOTO 19650
```

```
19600 GOSUB 20250:PRINT "Inadequate data. No regression can be performed.";:GOSUB 20890:GOTO 19580
19610 MKBACK=2:GOSUB 20350:CODE="GRAPHICS PACKAGE":GOSUB 20370:RETURN
19620 FOR J=0 TO 1:RESTORE 21620:FOR I=2 TO 23:READ A:LOCATE I,10+40*J:PRINT A;:NEXT I,J:RETURN
19630 INGA(1)=8:INGA(2)=2:INGA(3)=23:INGA(4)=1:INGA(5)=LMG:INGA(6)=15:INGA(7)=14:INGA(8)=2:INGA(15)=0
19640 GOSUB 17890:COLOR 15:RETURN
19650 COLOR 1,2:LOCATE 12,1:PRINT "Y-LABEL";:LOCATE ,40:PRINT "X-LABEL";
19660 PTR%=10:GOSUB 20250:COLOR 15,2:GOSUB 19620:LMG=10:GOSUB 19630:JGROUP=INDEX:GOSUB 20250
19670 FOOT=ALPHA+"vs.":LMG=50:GOSUB 19630:IGROUP=INDEX:FOOT=FOOT+ALPHA:GOSUB 18270:INDEX=40:PTR%=0
19680 GOSUB 19710:XMIN=PRMTR:GOSUB 19730:XMAX=PRMTR:XINC=(XMAX-XMIN)/10:INDEX=60
19690 GOSUB 19710:YMIN=PRMTR:GOSUB 19730:YMAX=PRMTR:YINC=(YMAX-YMIN)/10:X=XMIN
19700 K=1:WHILE K<=70:X=X+XINC/7:GOSUB 19440:K=K+1:WEND:ON IBMMONO+1 GOTO 19780,19890
19710 PRMTR=10000:FOR I=1 TO NOBS:IF RGP(INDEX+I)<PRMTR THEN PRMTR=RGP(INDEX+I)
19720 NEXT:RETURN
19730 PRMTR=0:FOR I=1 TO NOBS:IF RGP(INDEX+I)>PRMTR THEN PRMTR=RGP(INDEX+I)
19740 NEXT:RETURN
19750 '*
19760 '* COLOR GRAPHICS / HIGH RESOLUTION
19770 '*
19780 SCREEN 2:LINE (60,15)-(615,175),,B:GOSUB 19830:PSET (62,FNYAX(1))
19790 FOR I=2 TO 70:X=8*I+54:Y=FNYAX(I):LINE -(X,Y):NEXT:LOCATE 25,1:GOTO 19910
19800 '*
19810 '* SUBROUTINE #19
19820 '*
19830 LMG=IGROUP:GOSUB 20000:LOCATE 24,3:X=XMIN:FOR I=0 TO 10
19840 PRINT USING FMTGP;X;:X=X+XINC:NEXT:LMG=JGROUP:GOSUB 20000:Y=YMIN
19850 FOR I=22 TO 2 STEP -2:LOCATE I,1:PRINT USING FMTGP;Y;:Y=Y+YINC:NEXT:RETURN
19860 '*
19870 '* MONOCHROME GRAPHICS / ASCII
19880 '*
19890 CLS:INGA(11)=0:INGA(12)=22:INGA(13)=7:INGA(14)=79:GOSUB 20630:GOSUB 19830
19900 FOR J=1 TO 70:LOCATE FNMONY(J),8+J:PRINT "*";:NEXT:GOSUB 20260
19910 PRINT "End: Terminate  Home: Next ";CHR$(179);FOOT;
19920 A=INKEY$:IF LEN(A)=2 THEN A=RIGHT$(A,1) ELSE 19920
19930 IF A=CHR$(79) THEN CLOSE:GOSUB 19950:GOTO 19580
19940 IF A=CHR$(71) THEN GOSUB 19950:GOSUB 19610:GOTO 19650 ELSE 19920
19950 IF IBMMONO=0 THEN SCREEN 0,0,0:LOCATE ,,0
19960 RETURN
19970 '*
19980 '* GRAPHICS OUTPUT FORMAT
19990 '*
20000 RESTORE 20040:FOR I=1 TO LMG:READ ICOUNT:NEXT
20010 IF ICOUNT=1 THEN FMTGP=FMT10 ELSE IF ICOUNT=2 THEN FMTGP=FMT11 ELSE FMTGP=FMT12
20020 RETURN
20030 '* AXIS LABELS FORMAT CONSTANTS
20040 DATA 1,1,3,3,2,2,2,2,2,2,1,1,1,2,2,2,2,1,2,3,3,3
20050 '*
20060 '***************** SERVICE ROUTINES - GROUP 2 ***************************
20070 '* The following group of utility subroutines contains the most commonly
```

```
20080 '*  used subroutines to perform the various tasks.
20090 '*
20100 '* IMMEDIATE INTERRUPT
20110 GOSUB 20160:BEEP:GOSUB 20250:PRINT "Routine Interrupt upon request.";
20120 GOSUB 20890:COLOR ,2,2:CLOSE:GOSUB 20140:PTR%=0:IRQ=0:RETURN 10700
20130 '* ENABLE PF KEYS
20140 FOR I=1 TO 6:KEY(I) ON:NEXT:KEY(10) ON:RETURN
20150 '* DISABLE PF KEYS
20160 FOR I=1 TO 6:KEY(I) OFF:NEXT:KEY(10) OFF:RETURN
20170 '* ENABLE ARROWS
20180 FOR I=11 TO 14:KEY(I) ON:NEXT:RETURN
20190 '* DISABLE ARROWS
20200 FOR I=11 TO 14:KEY(I) OFF:NEXT:RETURN
20210 '* SAVE PARAMETERS
20220 SWAP J1,J1.BAK:SWAP J2,J2.BAK:SWAP J3,J3.BAK:SWAP PTR%,PTR.BAK%:RETURN
20230 '* CLEAR BOTTOM LINE(S)
20240 LOCATE 25,1:GOSUB 20270
20250 LOCATE 24,1:GOTO 20270
20260 LOCATE 25,1
20270 JROW=ROW%*100+COL%:ROW%=25:COL%=79:GOSUB 20670:COLOR MKBACK,MKBACK
20280 PRINT SPACE$(79);:COLOR 15:LOCATE ,1:ROW%=JROW\100:COL%=JROW MOD 100:RETURN
20290 '* CLEAR LINES 3 TO 22
20300 CALL CLRBFF:GOSUB 20320:RETURN
20310 '* FLAG DETECTION
20320 DEF SEG=0:POKE 1050,PEEK(1052):RETURN
20330 DEF SEG=0:IF PEEK(1047)=64 THEN RETURN ELSE POKE 1047,64:RETURN
20340 '* MAIN ROUTINE NEW PAGE
20350 COLOR ,MKBACK,MKBACK:CLS:GOSUB 20740:RETURN
20360 '* PRINT HEADERS
20370 LOCATE 1,1:GOSUB 20700:GOSUB 20330
20380 PRINT DATE$;TAB(17);TIME$;TAB(30);CODE;TAB(64);DD;FILEOUT;TAB(80);" ";:GOSUB 20720:RETURN
20390 '* PRINT MENUS
20400 COLOR 15:FOR I=J1 TO J2 STEP 2:READ A:LOCATE I,J3:PRINT A;:NEXT:RETURN
20410 '* CHECK FILE VALIDITY
20420 GOSUB 20250:PRINT "Defect section 2 in file ";FILEOUT;:GOSUB 20890:RETURN
20430 '* DATABASE TYPE
20440 IF DBASE%=2 THEN ALPHA="SIM_" ELSE ALPHA="ORD_":GOTO 20460
20450 IF MENU=2 OR MENU=3 OR MENU=6 THEN RETURN 10700
20460 RETURN
20470 '* DETERMINE FILEOUT
20480 FILEOUT=CTNO+ASYST+EXT1:GOSUB 20250:RETURN
20490 '* OPEN FILEOUT
20500 IF FILEOUT="" THEN RETURN 12770 ELSE FIN=DD+FILEOUT:GOSUB 20760
20510 IF FILETMP="" THEN IF A<>CHR$(27) THEN GOSUB 20610:GOTO 20500
20520 OPEN DD+FILEOUT AS #3:GOSUB 13560:RETURN
20530 '* OPEN DATABASE
20540 IF DBASE="" THEN RETURN 11790 ELSE FIN=DD+DBASE:GOSUB 20760
20550 IF FILETMP="" THEN IF A<>CHR$(27) THEN GOSUB 20610:GOTO 20540
```

```
20560 OPEN DD+DBASE AS #2:FIELD #2,2 AS FMARK:FIELD #2,28 AS FDIR1,12 AS FDIR2:RETURN
20570 '* SWITCH DATABASE
20580 GOSUB 20160:DD="":FILEOUT="":DBASE="":DBASE%=0:GOSUB 20140
20590 GOSUB 20320:GOSUB 20860:GOTO 12770
20600 '* ERROR DATABASE
20610 GOSUB 20250:BEEP:PRINT "Wrong database. Change diskette in drive ";DD;:GOSUB 20890:RETURN
20620 '* BORDERLINE
20630 LMG=MKBACK*16+15:CALL FRAME(LMG,INGA(11),INGA(12),INGA(13),INGA(14)):RETURN
20640 '* DETECT CURSOR LOCATION
20650 ROW%=CSRLIN:COL%=POS(0):RETURN
20660 '* DETECT COLOR
20670 MKBACK=SCREEN(ROW%,COL%,1)\16:MKFOR=SCREEN(ROW%,COL%,1) MOD 16:RETURN
20680 '* SET COLOR
20690 COLOR FNMC(15,0),FNMC(4,7):RETURN
20700 COLOR FNMC(14,0),FNMC(1,7):RETURN
20710 '* RESTORE COLOR
20720 GOSUB 20670:COLOR MKFOR,MKBACK:RETURN
20730 '* STORE SCREEN COLOR @ ROW=25 : COL=80
20740 GOSUB 20650:COLOR 15,MKBACK:LOCATE 25,79:PRINT CHR$(32);:LOCATE ROW%,COL%:RETURN
20750 '* ALLOCATE FILE(S)
20760 FOUT=SPACE$(12) 'CALL CHKDSK(DD,NREC):IF NREC>0 THEN ERROR 210 ELSE
20770 FILETMP="":CALL SEARCH(FOUT,FIN):IF FOUT=SPACE$(12) THEN 20790
20780 FILETMP=CHR$(ASC(LEFT$(FOUT,1))+64)+":"+MID$(FOUT,2,8)+"."+MID$(FOUT,10,3)
20790 RETURN
20800 '* UPDATE TIME
20810 GOSUB 20650
20820 GOSUB 20700:LOCATE 1,17:PRINT TIME$;:A=INKEY$:ON LEN(A)+1 GOTO 20820,20830,20840
20830 A=CHR$(ASC(A)+32*(ASC(A)>=97 AND ASC(A)<=122))
20840 GOSUB 20720:RETURN
20850 '* UPDATE ACTIVE FILE
20860 GOSUB 20700:LOCATE 1,64:PRINT SPACE$(14);
20870 LOCATE ,64:PRINT DD;FILEOUT;:COLOR ,FNMC(2,0):RETURN
20880 '* INPUT$(1)
20890 GOSUB 20320:GOSUB 20260:PRINT "Press any key to proceed.";:GOSUB 20810:GOSUB 20240:RETURN
20900 '* ON-LINE HELP & ON-LINE HELP INTERRUPT
20910 IRQ=1
20920 GOSUB 21430:CALL BUFFIN:MKBACK=3:GOSUB 20350:CLS:CODE="ON-LINE HELP":GOSUB 20370:GOSUB 20250:PAGE%=1
20930 PRINT "Home: Select page  End: Terminate HELP   PgUp: Previous page   PgDn: Next page";
20940 OFFPG=(PAGE%-1)*2:CALL HELP(OFFPG):LOCATE 1,64:GOSUB 20700:PRINT USING "PAGE      ##/10";PAGE%;
20950 GOSUB 20810:ON LEN(A) GOTO 20950,20960
20960 A=RIGHT$(A,1):IF A=CHR$(79) THEN 21030 ELSE IF A=CHR$(73) THEN 20990
20970 IF A=CHR$(81) THEN 21010 ELSE IF A=CHR$(71) THEN 21040
20980 BEEP:GOTO 20950
20990 PAGE%=PAGE%-1:IF PAGE%=0 THEN PAGE%=10
21000 GOTO 20940
21010 PAGE%=PAGE%+1:IF PAGE%=11 THEN PAGE%=1
21020 GOTO 20940
21030 GOSUB 20140:COLOR ,,2:IF IRQ=0 THEN GOTO 10700 ELSE CALL BUFFOUT:IRQ=0:RETURN
```

```
21040 GOSUB 20260:PRINT "Select page [  ]";:J1=25:J2=14:J3=2:GOSUB 17760
21050 PAGE%=VAL(ALPHA):IF PAGE%<1 OR PAGE%>10 THEN 21040 ELSE GOSUB 20260:GOTO 20940
21060 '* MAKE INTERRUPT LABEL
21070 COLOR ,2,2:CLS:GOSUB 20370:RETURN
21080 '* HELP KEYBOARD
21090 IRQ=1:GOSUB 21430:CALL BUFFIN:CODE="HELP KEYBOARD":GOSUB 21070
21100 CALL KEYBRD:GOSUB 20890:CALL BUFFOUT:GOSUB 21450:IRQ=0:RETURN
21110 '* HELP TRACTOR DIRECTORY
21120 IF DBASE="" THEN RETURN ELSE IRQ=1:CALL BUFFIN:GOSUB 21430
21130 KEY(3) ON:CODE="TRACTOR DIRECTORY":GOSUB 20370 '
21140 GOSUB 20300:GOSUB 20330:GOSUB 20540
21150 PTR%=5:GOSUB 20240:PRINT "Keyword, ENTER or ESC [              ]";
21160 J1=24:J2=24:J3=15:COLOR 15,2:GOSUB 17760:DIR=ALPHA
21170 IF DIR=CHR$(27) THEN ALPHA="":CLOSE:CALL BUFFOUT:GOSUB 21450:IRQ=0:RETURN ':LOCATE ROW%,COL%
21180 GOSUB 20240:IF DIR=CHR$(13) THEN PRINT "End: Terminate   PgUp: Previous page   PgDn: Next page";
21190 LGP=0:GET #2,1:LIMIT=CVI(FMARK):LIMIT=LIMIT\15:IF (LIMIT MOD 15)>0 THEN LIMIT=LIMIT+1
21200 L=1:NPAGE=1:ROW%=25:COL%=79:GOSUB 20670
21210 LOCATE 3,1:OFFPG=(NPAGE-1)*15+1:GET #2,1
21220 INGA(11)=2:INGA(12)=18:INGA(13)=14:INGA(14)=69:GOSUB 20630
21230 IF EOF(2) THEN 21310 ELSE OFFPG=OFFPG+1:GET #2,OFFPG:B=FDIR1:C=FDIR2
21240 IF DIR<>CHR$(13) THEN IF INSTR(B,DIR)=0 AND INSTR(C,DIR)=0 THEN 21230
21250 LGP=1:LOCATE 3+L,17:PRINT B,C:L=L+1:IF L=16 THEN L=1 ELSE 21230
21260 IF DIR=CHR$(13) THEN LOCATE 24,70:PRINT USING "Page ##";NPAGE; ELSE 21300
21270 GOSUB 20810:IF LEN(A)<2 THEN 21270
21280 A=RIGHT$(A,1):IF A=CHR$(79) THEN 21150 ELSE IF A=CHR$(73) THEN 21330
21290 IF A=CHR$(81) THEN 21350 ELSE 21270
21300 GOSUB 20250:PRINT "More...";:GOSUB 20890:COLOR 15:LOCATE 3,1:GOTO 21220
21310 IF LGP=0 THEN GOSUB 20260:PRINT "Record not found";:GOSUB 20250:GOTO 21150
21320 IF DIR=CHR$(13) THEN 21260 ELSE 21150
21330 COLOR 15:NPAGE=NPAGE-1:IF NPAGE=0 THEN NPAGE=LIMIT
21340 L=1:GOTO 21210
21350 COLOR 15:NPAGE=NPAGE+1:IF NPAGE>LIMIT THEN 21200 ELSE 21340
21360 '* ACTION DEPENDENT HELP
21370 IF PTR%=0 THEN RETURN ELSE IRQ=1:GOSUB 20160:NPAGE=(PTR%-1)*2
21380 CALL ACTION(NPAGE):GOSUB 20140:IRQ=0:RETURN ':LOCATE ROW%,COL%
21390 '* GET MAIN MENU
21400 IRQ=1:GOSUB 21430:CALL BUFFIN:INGA(11)=2:INGA(12)=20:INGA(13)=23:INGA(14)=56
21410 GOSUB 20630:GOSUB 10780:GOSUB 20890:CALL BUFFOUT:GOSUB 21450:IRQ=0:RETURN
21420 '* SAVE BUFFER
21430 GOSUB 20220:GOSUB 20160:GOSUB 20650:RETURN
21440 '* LOAD BUFFER
21450 GOSUB 20720:GOSUB 20140:GOSUB 20220:RETURN
21460 '*
21470 '***************************** END - GROUP 2 ****************************
21480 '*
21490 '* UTILITIES
21500 '*
21510 ANSR=DD
```

```
21520 MKBACK=2:GOSUB 20350:CODE="FILE HANDLING UTILITIES":GOSUB 20370
21530 COLOR 15,2:GOSUB 12230:RESTORE 21590:FOR I=5 TO 13 STEP 2:LOCATE I,28:READ A
21540 PRINT A;:NEXT:INGA(1)=7:INGA(2)=5:INGA(3)=13:INGA(4)=2:INGA(5)=28
21550 INGA(6)=15:INGA(7)=14:INGA(8)=2:INGA(15)=0:GOSUB 17890:BTIME=TIME$:NREC=0:NERR=0
21560 COLOR ,2,2:ON INDEX GOTO 21730,22270,23140,21520,21570
21570 DD=ANSR:FILETMP="":GOTO 10680
21580 '* LABELS FOR THE UTILITIES
21590 DATA " Tractor library utility "," Tire management utility "," File management utility "
21600 DATA " User definable program  "," Terminate utilities: MM "
21610 '* LABELS FOR THE GRAPHICS MENU
21620 DATA " Efficiency Force        "," Efficiency Tractive     "," Engine RPM            "
21630 DATA " Gear Setting            "," Motion Resistance       "," Pull Drawbar          "
21640 DATA " Power Axle              "," Power Coefficient       "," Power Drawbar         "
21650 DATA " Power PTO               "," Ratio Dynamic Traction "," Ratio Gross Traction  "
21660 DATA " Ratio Travel            "," Slip                    "," Speed Actual          "
21670 DATA " Speed Theoretical       "," Thrust Gross            "," Tire effective arm    "
21680 DATA " Torque                  "," Weight Front Dynamic  "
21690 DATA " Weight Rear Dynamic     "," Weight Transfer       "
21700 '*
21710 '* TRACTOR LIBRARY UTILITY
21720 '*
21730 CLS:CODE="TRACTOR LIBRARY UTILITY":GOSUB 20370:NREC=0:GOSUB 23400:COLOR 15:IDERR=1
21740 J1=3:J2=36:J3=3:LOCATE 3,1:PRINT "Specify major data file [A:TRACTOR.   ]";
21750 PTR%=11:GOSUB 23440:EXT1=ALPHA:FILE1="A:TRACTOR."+EXT1:J1=4:J2=40:J3=1
21760 LOCATE 4,1:PRINT "Define the unit system of output file [ ]";:GOSUB 23440
21770 UNIT%=VAL(ALPHA):IF UNIT%=1 THEN RESTORE 11740 ELSE IF UNIT%=2 THEN RESTORE 11750 ELSE 21760
21780 READ ASYST,APL:J1=5:J2=39:J3=3:LOCATE 5,1:LGP=0
21790 PRINT "Specify number of records to process [   ]";:GOSUB 23440
21800 OREC=VAL(ALPHA):IF OREC<1 THEN MREC=1:OREC=999:LGP=-1:GOTO 21910
21810 LOCATE 6,1:J1=6:J2=34:PRINT "Specify first record to process [   ] :";
21820 GOSUB 23440:IF ALPHA="?" THEN GOSUB 20220:J1=24:J2=21:J3=26 ELSE 21900
21830 PTR%=12:GOSUB 20250:PRINT "Enter tractor name [                          ]";
21840 GOSUB 23440:ICOUNT=0:OPEN FILE1 FOR INPUT AS #1:GOSUB 20250
21850 WHILE NOT EOF(1):ICOUNT=ICOUNT+1:INPUT #1,JOBN,NOBS,DESIGN,RATPWR,IFPLY,IRPLY,LAB
21860 IF INSTR(DESIGN,ALPHA)>0 THEN MREC=ICOUNT:GOTO 21890
21870 FOR I=1 TO NOBS+6:LINE INPUT #1,A:NEXT
21880 WEND:PRINT "Tractor ";DESIGN;" was not found.";:MREC=1
21890 PRINT "First record set to";MREC;:GOSUB 20890:CLOSE #1:GOSUB 20220:GOTO 21820
21900 IF ALPHA="" THEN 21910 ELSE MREC=ABS(VAL(ALPHA))
21910 LOCATE 8,1:PRINT "Insert source diskette in drive A"
21920 PRINT "Insert target diskette in drive B":IF MREC=0 THEN MREC=1
21930 PRINT "Press any key to proceed":A=INPUT$(1):IF A=CHR$(27) THEN GOSUB 23450
21940 FILE2="B:ORD_"+ASYST+"."+EXT1:PTR%=0:FIN=FILE1:GOSUB 22230
21950 OPEN FILE1 FOR INPUT AS #1:ICOUNT=0:FIN=FILE2:GOSUB 20760
21960 OPEN FILE2 AS #2:FIELD #2,2 AS BOUND:FIELD #2,28 AS FLD1,12 AS FLD2
21970 IF FOUT="" OR LGP=-1 THEN MARK=0 ELSE GET #2,1:MARK=CVI(BOUND)
21980 LOCATE 12,1:COLOR 11:PRINT "Wait! Record processing is in progress..."
21990 IF UNIT%=2 THEN PRINT "Metric to Imperial system Conversion (MIC)"
```

```
22000 WHILE NOT EOF(1):A=INKEY$:IF A=CHR$(27) THEN GOSUB 23450
22010 ICOUNT=ICOUNT+1:INPUT #1,JOBN,NOBS,DESIGN,RATPWR,IFPLY,IRPLY,LAB
22020 IF ICOUNT>=MREC THEN LOCATE 16,1:GOTO 22050
22030 FOR I=1 TO NOBS+6:LINE INPUT #1,A:NEXT:LOCATE 14,1
22040 PRINT "Record";ICOUNT;"skipped...":GOTO 22190
22050 INPUT #1,ALOC,CTNO,DATE,FSURF,DFRONT,DREAR
22060 INPUT #1,PF,PR,SFWT,STOWT,TDBH,WHLBS,NUMR,NUMF,OPRPM
22070 FOR I=1 TO 14:INPUT #1,INGA(I):NEXT:FOR I=41 TO 54:INPUT #1,RGP(I):NEXT
22080 FOR I=1 TO NOBS:INPUT #1,TDBPWR(I),PULL(I),VA(I),SLIP(I),IRPM(I),NGR(I):NEXT
22090 IF UNIT%=1 THEN 22120 ELSE RATPWR=RATPWR*1.34:PF=PF*.145:PR=PR*.145
22100 SFWT=SFWT*2.2:STOWT=STOWT*2.2:WHLBS=WHLBS*39.37:TDBH=TDBH*39.37
22110 FOR I=1 TO NOBS:PULL(I)=PULL(I)*225:TDBPWR(I)=TDBPWR(I)*1.34:VA(I)=VA(I)*.6215:NEXT
22120 FILE3=CTNO+ASYST+"."+EXT1:PRINT USING "Tractor \                                  \";DESIGN;
22130 PRINT USING "with filename \            \";FILE3:PRINT
22140 OPEN "B:"+FILE3 AS #3:GOSUB 12230:GOSUB 13770:CLOSE #3
22150 PRINT "Record ";FILE3;" has been processed.":PRINT
22160 IF LGP=-1 THEN LSET FLD1=DESIGN:LSET FLD2=FILE3:PUT #2,ICOUNT+1 ELSE GOSUB 17630
22170 PRINT "Record ";FILE3;" has been written to ";FILE2
22180 IF ICOUNT=OREC THEN CLS:GOTO 22200
22190 WEND:CLS:GOSUB 20370:PRINT "End of file (EOF)"
22200 NREC=NREC+ICOUNT:MARK=MARK+ICOUNT:RSET BOUND=MKI$(MARK):PUT #2,1:CLOSE
22210 GOSUB 20250:PRINT "Repeat or Exit (R/E) ?";
22220 GOSUB 20810:IF A="R" THEN 21730 ELSE IF A="E" THEN 23500 ELSE 22220
22230 GOSUB 20760:IF FILETMP="" THEN GOSUB 20610:GOTO 22230 ELSE RETURN
22240 '*
22250 '* TIRE LIBRARY UTILITY
22260 '*
22270 CLS:GOSUB 20200:CODE="TIRE LIBRARY UTILITY":GOSUB 20370
22280 COLOR 15:RESTORE 22870:FOR I=0 TO 3:READ A:LOCATE 4,2+13*I:PRINT A;:NEXT
22290 INGA(1)=9:INGA(2)=4:INGA(3)=7:INGA(4)=1:INGA(5)=2:INGA(6)=15:INGA(7)=14
22300 INGA(8)=2:INGA(15)=1:GOSUB 17890:ON INDEX GOTO 22310,22520,22930,23500
22310 J1=7:J2=33:J3=14:GOSUB 23400:LOCATE 7,1:PRINT "Enter source    filename [.DAT]: ";
22320 GOSUB 23570:IF EXT1="" THEN EXT1=".DAT"
22330 FILE1=DD+FILE0+EXT1:J1=8:J2=32:J3=1:PRINT "Enter destination drive [";DD;"] :";
22340 GOSUB 23570:IF ALPHA="" THEN 22350 ELSE DD=ALPHA+":"
22350 FILE2=DD+FILE0+".DIR":FILE3=DD+FILE0+".RND"
22360 IF FILE1=FILE3 OR FILE1=FILE2 THEN CLS ELSE 22380
22370 COLOR 15:PRINT "File designation Error.":COLOR 14:GOTO 22320
22380 GOSUB 20250:PRINT "Replace diskettes.";:GOSUB 20890:IF A=CHR$(27) THEN GOSUB 23450
22390 OPEN FILE1 FOR INPUT AS #3:OPEN FILE2 AS #1:OPEN FILE3 AS #2:GOSUB 13710
22400 I=0:COLOR 11:LOCATE 12,1:PRINT "Source and Object files have been opened."
22410 A=INKEY$:IF A=CHR$(27) THEN GOSUB 23450 ELSE IF EOF(3) THEN NREC=I ELSE 22430
22420 RSET BOUND=MKI$(NREC):PUT #1,1:GOTO 22490
22430 I=I+1:INPUT #3,CLASS,CODE,IPLY,TRF,LDF,IPF,TWF,TDF,B
22440 LOCATE 15,1:PRINT "Record";I;"has been read  from  ";FILE1
22450 RSET CNT=MKI$(I):LSET CL=CLASS:RSET CD=CODE:RSET APR=MKI$(IPLY):PUT #1,I+1
22460 RSET ATR=MKS$(TRF):RSET ATL=MKI$(LDF):RSET ATI=MKI$(IPF):RSET ATW=MKS$(TWF)
22470 RSET ATD=MKS$(TDF):RSET DUMMY=B:PUT #2,I:PRINT
```

```
22480 PRINT "Record";I;"has been written to  ";FILE2;" and ";FILE3:GOTO 22410
22490 CLS:COLOR 15:PRINT:PRINT "End of data file (EOF).":CLOSE
22500 PRINT "All files are closed.":GOTO 23500
22510 '*
22520 '* READ TIRES
22530 '*
22540 GOSUB 20260:I=1:PRINT "Select tire file [A:        .RND]"
22550 J1=25:J2=21:J3=8:GOSUB 23570
22560 FILE2="A:"+FILEO+".RND":FILE1="A:"+FILEO+".DIR":FIN=FILE1:GOSUB 22230
22570 OPEN FILE1 AS #1:OPEN FILE2 AS #2:GOSUB 13710:LOCATE 10,1:NREC=1
22580 PRINT "Unit system    #    Radius    Load    Pressure    Width   Diameter"
22590 GOSUB 20240:PRINT "PgUp: Previous record  PgDn: Next record  Home: Search record  End: Terminate";
22600 GOSUB 13710:GET #1,1:LIMIT=CVI(BOUND)
22610 COLOR 15:GET #1,NREC+1:GET #2,NREC:IPLY=CVI(APR)
22620 LOCATE 8,1:PRINT "Tire ";CD;":";IPLY;":";CL;"  ":LOCATE 12,1:PRINT "IMPERIAL   :";
22630 TRR=CVS(ATR):TWR=CVS(ATW):TDR=CVS(ATD):LDR=CVI(ATL):IPR=CVI(ATI)
22640 GOSUB 22720:PRINT "METRIC (SI):";:GOSUB 11700:GOSUB 22720
22650 GOSUB 20810:ON LEN(A) GOTO 22650,22660
22660 A=RIGHT$(A,1):IF A=CHR$(73) THEN 22700 ELSE IF A=CHR$(81) THEN 22680
22670 IF A=CHR$(71) THEN 22760 ELSE IF A=CHR$(79) THEN CLOSE:GOTO 22270 ELSE 22650
22680 IF NREC=LIMIT THEN BEEP:NREC=1 ELSE NREC=NREC+1
22690 GOTO 22610
22700 IF NREC=1 THEN BEEP:NREC=LIMIT ELSE NREC=NREC-1
22710 GOTO 22610
22720 PRINT USING " ###";NREC;:PRINT USING " #####.## ";TRR;LDR;IPR;TWR;TDR:RETURN
22730 '*
22740 '* SEARCH
22750 '*
22760 COLOR 10:ICOUNT=NREC:GOSUB 20250
22770 PRINT "Specify tire code to be searched :";:J1=24:J2=36:J3=8:GOSUB 23440
22780 CODE=ALPHA:GOSUB 20250:J1=24:J2=45:J3=2:IF LEN(CODE)=7 THEN CODE=" "+CODE
22790 PRINT "Specify tire ply rating or ENTER for none :";:GOSUB 23440
22800 IPLY=VAL(ALPHA):NREC=1:GOSUB 20260:PRINT "Searching.....";:COLOR FNMC(14,0),FNMC(2,7)
22810 WHILE NOT EOF(1):GET #1,NREC+1:I=CVI(APR):LOCATE 25,20:PRINT " ";CD;":";I;
22820 IF CODE=CD AND (IPLY=0 OR IPLY=I) THEN 22830 ELSE NREC=NREC+1:WEND
22830 COLOR 15,FNMC(2,0):IF NREC>LIMIT THEN GOSUB 20250 ELSE 22610
22840 PRINT "Record ";CODE;":";IPLY;" was not found.";:GOSUB 20890
22850 NREC=ICOUNT:GOSUB 20240:GOTO 22650
22860 '*
22870 DATA Library,Read,Write,Terminate
22880 DATA "Tire size","Tire ply","Tire type","Static radius","Maximum load"
22890 DATA "Maximum pressure","Tire diameter","Tire width","Tangential pull"
22900 '*
22910 '* WRITE TIRE RECORD
22920 '*
22930 OPEN "A:USER.DIR" AS #1:OPEN "A:USER.RND" AS #2:GOSUB 13710:NREC=1:GET #1,1
22940 LIMIT=CVI(BOUND):RESTORE 22880:J3=15:FOR I=1 TO 3:FOR J=0 TO 2:J1=I+9:J2=J*27
22950 READ A:LOCATE J1,J2:PRINT A;" :";:J2=J2+LEN(A)+3:GOSUB 20250:E(I*3+7+J)=ALPHA:NEXT J,I
```

```
22960 CODE=E(10):RSET CD=CODE:CODE=CD:IPLY=VAL(E(11)):CLASS=E(12):TRR=VAL(E(13))
22970 LDR=VAL(E(14)):IPR=VAL(E(18)):TDR=VAL(E(16)):TWR=VAL(E(17)):ICOUNT=VAL(E(18))
22980 WHILE NOT EOF(1):GET #1,NREC+1:IF CODE>CD THEN 23010
22990 IF CODE<CD THEN 23020 ELSE IF IPLY>CVI(APR) THEN 23010
23000 IF IPLY<CVI(APR) THEN 23020 ELSE GOSUB 20240:PRINT "Tire ";CODE;":";CD;" exists";:GOSUB 20890:GOTO 22290
23010 NREC=NREC+1:WEND
23020 E(1)=CL:E(2)=CD:E(3)=APR:GET #2,NREC:E(4)=ATR:E(5)=ATL:E(6)=ATI:E(7)=ATD
23030 E(8)=ATW:E(9)=DUMMY:RSET CNT=MKI$(NREC):LSET CL=CLASS:RSET CD=CODE
23040 RSET APR=MKI$(IPLY):PUT #1,NREC+1:RSET ATR=MKS$(TRR):RSET ATL=MKI$(LDR)
23050 RSET ATI=MKI$(IPR):RSET ATD=MKS$(TDR):RSET ATW=MKS$(TWR):RSET DUMMY=MKI$(ICOUNT):PUT #2,NREC
23060 WHILE NOT EOF(1):NREC=NREC+1:GET #1,NREC+1:GET #2,NREC:GOSUB 23080:WEND
23070 GOSUB 23080:RSET BOUND=MKI$(NREC):PUT #1,1:CLOSE:GOTO 23500
23080 SWAP E(1),CL:SWAP E(2),CD:SWAP E(3),APR:SWAP E(4),ATR:SWAP E(5),ATL
23090 SWAP E(6),ATI:SWAP E(7),ATD:SWAP E(8),ATW:SWAP E(9),DUMMY:CNT=MKI$(NREC)
23100 PUT #1,NREC+1:PUT #2,NREC:RETURN
23110 '*
23120 '* FILE MANAGER
23130 '*
23140 I=1:LMG=2
23150 CLS:CODE="FILE MANAGER":GOSUB 20370:COLOR 15:RESTORE 23350:FOR I=0 TO 2
23160 READ A:LOCATE 4,2+13*I:PRINT A;:NEXT:INGA(1)=10:INGA(2)=4:INGA(3)=6
23170 INGA(4)=1:INGA(5)=2:INGA(6)=15:INGA(7)=14:INGA(8)=2:INGA(15)=1:GOSUB 17890
23180 COLOR 14:J3=14:ON INDEX GOTO 23220,23220,23500
23190 '*
23200 '* COPY AND RENAME FILES
23210 '*
23220 IF INDEX=1 THEN A="Copy":B=" copied to " ELSE A="Rename":B=" renamed as "
23230 INGA(11)=8:INGA(12)=20:INGA(13)=0:INGA(14)=78:GOSUB 20630:ICOUNT=0:COLOR 15
23240 LOCATE 11,5:PRINT A;"....":J1=13:J2=21:J3=14
23250 LOCATE 13,5:PRINT "from : ";:GOSUB 23570:FILE1=DD+FILE0+EXT1:J1=15
23260 LOCATE 15,5:PRINT "to   : ";:GOSUB 23570:FILE2=DD+FILE0+EXT1
23270 LOCATE 17,5:PRINT "File ";FILE1;" is to be";B;FILE2;". Verify (Y/N)";
23280 GOSUB 20810:IF A="Y" THEN 23300 ELSE IF A="N" THEN 23140 ELSE 23280
23290 ON INDEX GOTO 23300,23320
23300 OPEN FILE1 FOR INPUT AS #1:OPEN FILE2 FOR OUTPUT AS #2
23310 IF EOF(1) THEN 23330 ELSE A=INPUT$(1,#1):PRINT #2,A;:GOTO 23310
23320 NAME FILE1 AS FILE2
23330 CLOSE:LOCATE 19,5:PRINT "File ";FILE1;B;FILE2;
23340 GOSUB 20890:GOTO 23140
23350 DATA Copy,Rename,Terminate
23360 GOSUB 20250:PRINT "Arrows: Select Option     End: Execute Option";:RETURN
23370 '*
23380 '* UTILITIES INTERRUPT
23390 '*
23400 GOSUB 20250:PRINT "Press ESC to interrupt the process";:COLOR 14:RETURN
23410 '*
23420 '* ESC
23430 '*
```

```
23440 GOSUB 17760
23450 IF ALPHA=CHR$(27) THEN BEEP ELSE RETURN
23460 PTR%=0:GOSUB 20300:COLOR 15:LOCATE 3,1:PRINT "Immediate interrupt upon request.":RETURN 23510
23470 '*
23480 '* TERMINATE
23490 '*
23500 GOSUB 20300:COLOR 15:LOCATE 3,1:PRINT "Program terminated normally."
23510 CLOSE:LOCATE 10,1:PRINT "  Begining @ :";BTIME:PRINT "  End       @ :";TIME$
23520 LOCATE 15,1:PRINT USING " ### records were processed.";NREC
23530 PRINT USING " ### errors encountered.";NERR:GOSUB 20250:GOSUB 20890:GOTO 21520
23540 '*
23550 '* CHECK FILENAME SYNTAX
23560 '*
23570 DD="":EXT1="":GOSUB 17760:IF ALPHA=CHR$(27) THEN BEEP:GOTO 23460
23580 I=FNLSTR(ALPHA,DATA1):J=FNLSTR(ALPHA,DATA2):IF LEN(ALPHA)=I THEN 23570
23590 IF I=0 THEN DD="A:" ELSE DD=LEFT$(ALPHA,2)
23600 IF J=0 THEN J=LEN(ALPHA)+1 ELSE EXT1=MID$(ALPHA,J,LEN(ALPHA)+1-J)
23610 I=I+1:FILE0=MID$(ALPHA,I,J-I):RETURN
23620 '*
23630 '* ERROR HANDLING SUBROUTINE
23640 '*
23650 NERR=NERR+1:BEEP:GOSUB 20250
23660 IF ERR=5 THEN 23670 ELSE 23690
23670 IF ERL=10640 THEN RESUME 10640 ELSE IF ERL=10650 THEN RESUME 10650
23680 IF ERL=10260 OR ERL=19900 THEN 23800 ELSE IF ERL=16770 THEN 23810 ELSE 23740
23690 IF ERR=6 OR ERR=11 THEN 23750
23700 IF ERR=61 THEN 23760
23710 IF ERR=68 OR ERR=25 THEN 23780
23720 IF ERR=210 THEN 23770
23730 IF ERR=200 THEN 23790
23740 CLS:PRINT "Error number:";ERR:PRINT "Error line:";ERL:GOSUB 20890:CLOSE:RESUME 10730
23750 PRINT "Overflow @ line";ERL;:GOSUB 20890:CLOSE:RESUME 10730
23760 PRINT "Disk in drive ";DD;" is full.";:GOSUB 20890:CLOSE:RESUME 10700
23770 PRINT "Disk drive ";DD;" is not ready.";:GOSUB 20890:RESUME 20760
23780 PRINT "There is no printer connected.";:GOSUB 20890:RESUME 15240
23790 PRINT "Unexpected input @ line ";ERL;:GOSUB 20890:CLOSE:RESUME 10700
23800 LPRINT ERL,XMIN,XMAX,YMIN,YMAX:FOR J=1 TO 70:LPRINT XMIN+(J-1)*XINC/7,RGP(J):NEXT:GOSUB 20810:RESUME 10730
23810 LOCATE 22,20:PRINT "WAIT";:A=INPUT$(1):RESUME 10730
23820 '*
23830 '* END OF PROGRAM
23840 '*
```

## Programmer's note

The BASIC program presented is the High-Level language part of the integrated package. In addition to the High-Level language source code, nine Assembly language modules were programmed and Linked to the compiled BASIC program. The nine Assembly language modules are an integrated part of the software. The program may NOT run without the Assembly language modules.

Both BASIC and Assembly language source code have been submitted to the Department of Agricultural Engineering of the University of Alberta.